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SUSTAINABLE WOODEN BUILDING CONCEPT FOR CENTRAL JAPAN

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YUTAKA GOTO

MS. Agr., The University of Tokyo

born November 17th 1984

citizen of Japan

accepted on the recommendation of

Prof. Dr. Holger Wallbaum, examiner

Dr. Karim Ghazi Wakili, co-examiner

Prof. Dr. Naoto Ando, co-examiner

Prof. Dr. Mario Fontana, co-examiner

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PAPERS OF THE DISSERTATION

Paper I:

Goto Y., Ghazi Wakili K., Ostermeyer Y., Frank T., Ando N., Wallbaum H.: “Preliminary investigation of a vapor-open envelope tailored for subtropical climate”. *Building and Environment* 46(3): 719-728, 2011.

Paper II:

Goto Y., Ghazi Wakili K., Frank T., Stahl T., Ostermeyer Y., Ando N., Wallbaum H.: “Heat and moisture balance simulations of a building with vapor-open envelope system for subtropical regions”. *Building simulation* 5(4): 301-314, 2012.

Paper III:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

In light of the high probability of global warming, the mitigation of climate change is one of the most urgent issues. As long as human society is expected to grow further, the fundamental philosophy of technology development must be based on sustainability. Developing technologies should not deteriorate the equal opportunity for people to continue growing through time and space.

Under such global agreement, the major issues are resource depletion and the rapid growth of developing regions. Even though the rational use of resources has been intensively discussed, the utilization of renewable resources has not been fully implemented yet. Among many renewable resources, wood is of high importance because of its diverse usages and its ability to absorb and store CO_2. Also very related to the issue of resource consumption, the growth of developing regions has a significant impact on the environment and human society on a global scale. These urban developments need to be supported by sustainable measures. It should be noted that large parts of such emerging economies are situated in subtropical regions. Hence, solutions to deal with subtropical conditions are increasingly needed.

Today it is widely recognized that the construction industry is playing a key role in both resource depletion and urbanization of developing regions. Rational management of construction activities and buildings may have significant impact on mitigating climate change. Among other aspects, the selection of construction methods and materials and the advancement of energy efficiency are key points to consider. In the field of energy efficiency of buildings, there have been numerous studies and many technologies have already been in practical use for some time. The state-of-art building technology is super-insulated and airtight buildings, which are often a hybrid of passive (driven by no energy consumption) and active (driven by active energy consumption) measures. Those technologies have been developed based on experiences in primarily cold/mild climatic regions.

Considering the issues addressed above and the proportion of the country characterized by a subtropical climate, Japan has great potential for improving its construction industry from a sustainability viewpoint, especially given its market size (e.g. 1 000 000 newly-built houses in 2008) and its rather backward energy standard. When developing new construction methods, the following points should be considered thoroughly.

Japan has diverse climatic conditions due to its geographic characteristics. The northern regions have a continental climate similar to central/northern European conditions, while the central and southern regions have a subtropical climate. It is divided into six climate-zones in accordance with the Japanese law on the rational use of energy in the housing sector. This climatic diversity should be carefully taken into account as much as possible when discussing the design of a building.

The use of domestic forest resources is another important issue for Japan. Although 93% of the detached houses in the housing stock (2008) are wooden constructions and 66% of the land is covered by forest, the self-sufficiency rating of wood (including paper/pulp and others) is only around 26% (2010). An extensive forestation program was carried out as a national policy after the Second World War in order to secure the supply of the raw material. Nowadays those densely planted forests are causing environmental damage to the ecosystem such as decreasing the capacity of CO_2 storage, increasing the risk of landslides and so on. At the same time the economy of domestic forestry has been going through long-term depression due to the low cost of imported timber. For conducting sustainable forest management, it is absolutely necessary to come up with measures which stimulate the forestry economy by creating profit. The key is to add value even to the unprofitable forest products such as the thin timbers.

The latest effort in the Japanese housing industry can be characterized by two measures, namely employing foreign technologies especially for energy efficiency and high-tech housing services, such as sophisticated heat pumps, fuel cells and so on. As for the implementation of foreign technologies, the rather rapid change by direct transfer without sufficient consideration on the local climatic conditions as well as socio-cultural aspects have resulted in problems regarding building physics and conflicts in terms of social acceptance. As the Japanese government plans to implement obligatory regulation on energy efficiency for all buildings in the coming decade, there is a strong need to develop building technologies which soundly deal with both the subtropical climate and socio-cultural aspects. Considering the need for utilizing domestic timber and the already well-developed housing service technologies, a novel wooden building envelope, which ensures the rational use of resource and energy efficiency, may be one such sound solution.

In order to deal with the issues, a vapor-open wood-based building envelope system was developed within the research and development project funded by the Commission for Technology and Innovation (grant number: 9755.1 PFIW-IW). The envelope consists mainly of layers of natural materials, namely an external insulation layer of wood fiber board, a structural layer of cross laminated timber consisting of slats with small section and an interior finishing layer composed of a wood and clay composite. Each component is made of hygroscopic material with moderate vapor permeability. Therefore the system allows the moisture flux to move through the wall in both directions. Also the thickness of each layer can be determined regardless of the other layers. These features solve the moisture related problems inside exterior walls under subtropical conditions. Besides the considerations regarding building physics, the design philosophy of the envelope also comprises ecological, economic and social aspects. The components are based on natural materials, and so it may be produced using local resources. Local production also promotes the local economy creating a local value chain. The local climatic conditions and socio-cultural aspects, such as user behaviors, can be taken into account by the flexibility assured by the layered structure.

In this thesis the building physics, economic and ecological performance of the envelope system under Japanese conditions was quantitatively assessed. The specific purpose was to evaluate the feasibility of the envelope system for implementation in the Japanese market. At the same time, the application of the evaluation method developed within this dissertation on other construction methods and in other regions was also considered.

The verification of the system's overall performance was carried out within an interdisciplinary framework. Firstly, in order to investigate the durability, the hygrothermal performance of the envelope was analyzed with a transient heat and moisture transfer model. This model was validated by experiments with full-scale wall specimens. Secondly, in order to investigate the energetic performance of a building with this envelope system, a model was created to simulate the indoor temperature, relative humidity and the heating/cooling demand, combining the hygrothermal model of the envelope itself, heat balance model of the whole building and the moisture balance model, taking into account the interaction of the envelope and ambient air. Finally, in order to investigate the feasibility of applying the envelope system to Japanese conditions, a model was created to define the economic and ecological optimal insulation thickness, using the transmission heat loss model described above, simplified Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) methods. In the optimization model several scenarios were considered for taking the uncertainty of the future economic situation into account.

This thesis is a cumulative dissertation, and consists of six chapters. Chapter 1 presents the overall background and the goal of the study. In section 1.1, a general concept of sustainability in technology development is presented as an orientation with which to begin the study, and then global issues in the construction sector and the rapid economic growth in subtropical regions are introduced. In section 1.2, the specific conditions of the Japanese housing industry are elaborated upon in order to highlight particular problems. In Chapter 2, the detailed design philosophy of the envelope system is introduced, and finally the methodologies for evaluating its performance from the viewpoints of building physics, economics and ecology are introduced by reviewing past studies.

The three following chapters (3, 4 and 5) consist of three research papers (Paper I, II and III). Chapter 3 presents Paper I, which was published in a peer-reviewed scientific journal (*Paper I: Building and Environment - Preliminary Investigation of a Vapor-open Envelope Tailored for Subtropical Climate*). Chapter 4 presents Paper II, which was published in a peer-reviewed scientific journal (*Paper II: Building Simulation - Heat and Moisture Balance Simulation of a Building with Vapor-open Envelope System for Subtropical Regions*). Chapter 5 presents Paper III, which was published in a peer-reviewed scientific journal (*Paper III: Energy and Buildings - Economic, Ecological and Thermo-hygric Optimization of a Vapor-open Envelope for Subtropical Climates*).

In Chapter 3 (Paper I), the hygrothermal performance of the envelope system, investigated by means of testing full-scale walls in a climate chamber, and the corresponding one-dimensional transient heat and transfer simulation are presented. In order to maintain consistency between calculation and measurement, the individual materials were tested for their hygric and thermal properties. The results in Chapter 3 show that the experiment and the numerical simulation corresponded to each other with high accuracy. Based on these findings, attempts were made to calculate the behavior of a wall assembly under real climatic conditions of central Japan, Kyoto. As a result, it was shown that no risk of interstitial condensation and mold growth was predicted under the real climatic conditions of Kyoto.

In Chapter 4 (Paper II), the heat and moisture balance model of a building with the envelope system is proposed. In the moisture balance model the moisture buffering by the interior materials was taken into account in addition to the standard factors, such as air infiltration, indoor moisture load due to human activities, etc. The prediction of the moisture buffer value (MBV) of the interior finishing materials was attempted and validated by empirical data. Subsequently, the whole building calculation was carried out under the condition of a Japanese city, Hikone, and energy consumption and the contribution of the moisture buffering to indoor comfort was investigated. The results of Chapter 4 are as follows. The MBVs of the mineral-based materials were predicted with high accuracy. However the MBVs of the wood-based composite were much higher than the experimental value. In order to create a more accurate MBV prediction model, nonlinear moisture conductance on the fiber scale should be taken into account when modeling wood-based materials. The heating and cooling demand of a test house was 9.4 kWh/m^2 and 14.5 kWh/m^2 respectively. The moisture buffering contributed to a significant reduction of humidity fluctuation. It was concluded that the envelope system can be implemented to provide highly energy efficient buildings under subtropical conditions. In order to enhance both energy efficiency and indoor comfort of buildings in subtropical regions, there is still a strong need to develop a more holistic method for finding the optimum building design, considering not only moisture buffering by interior materials but also all the relevant factors, such as shading, active dehumidification and so on.

In Chapter 5 (Paper III), the optimal insulation thickness of a building with the envelope system was investigated under the conditions of eight cities in Japan by an economic and ecological model, taking into account both initial and running cost. The basic intention was to define the optimal insulation thickness of a building dealing with the trade-off between economic and ecological performance ("the thicker the insulation is, the less heating energy is consumed and the more material is used"). The thermo-hygric minimum thickness was also determined in order to ensure the longevity of the buildings. The transmission heat loss model for those simulations was based on the whole building model proposed in Chapter 4. Consequently, the following main findings were made: 1) the ecological optimal thickness was larger than the economic optimal thickness, 2) the thermo-hygric minimum was within the economic optimal range in most of the cases, and 3) the interest rate of the currency and the electricity price increase have a significant influence on the result of the optimization analysis. With the aid of the optimization model, it was shown that applying this envelope system is feasible in Japan, especially in the central and southern regions.

Finally the overall conclusion of the thesis is given in Chapter 6, summarizing and discussing the findings and discussions in Chapter 3 to 5. The main conclusions were made as follows:

- The hygrothermal performance of the envelope system was modeled and validated successfully.
- With the aid of the heat and moisture balance model suggested, it was made possible to predict indoor temperature, relative humidity and heating/cooling demand, and the envelope system can be used for providing highly energy efficient building under subtropical conditions.
- With the aid of the insulation optimization model proposed, it was shown that implementing the envelope system is feasible in Japan, especially in the central and southern regions.

However, there remain several deficits to be improved upon in the models, such as the inadequacy of the hygrothermal model with wind driven rain, the limitation of the modeled volume in the whole building simulation and limited parameters in the optimization model on local conditions (material price, energy mix, etc.). There is potential for expanding the overall model by optimizing the insulation thickness and housing service setting for dealing with the trade-off between the energy consumption and indoor comfort.

It was concluded that the envelope system proposed in this study has a high potential for implementation in central Japan to enhance the sustainability of the Japanese housing industry. It is also applicable to other regions that have similar climatic conditions. The modeling methods (the whole building hygrothermal model and the insulation thickness optimization model) can be applied to other construction methods with minor adjustments. The whole building hygrothermal model will be validated by empirical data from a test house in the future (anticipated construction in Ohmihachiman in May 2013).

ZUSAMMENFASSUNG

Angesichts der zu erwartenden globalen Erwärmung ist die Abmilderung des Klimawandels eine der drängendsten Aufgaben. So lange wie die Gesellschaft weiter wächst, muss Nachhaltigkeit daher die Grundlage der technologischen Entwicklung sein. Die Entwicklung der Technologien sollte dabei die Chancengleichheit der Menschen für weiteres Wachstum unabhängig von Zeit und Ort gewährleisten.

Unter diesen globalen Randbedingungen sind die grössten Herausforderungen die Ausbeutung der nicht nachwachsenden Rohstoffe und der schnelle Wachstum der Entwicklungs- und Schwellenländer. Obwohl der vernünftige Einsatz der Rohstoffe bereits ausgiebig diskutiert wurde, ist eine Verwendung erneuerbarer Rohstoffe bisher noch nicht zu ihrem vollen Potential implementiert. Neben vielen anderen erneuerbaren Rohstoffen ist Holz aufgrund seiner vielfältigen Einsatzmöglichkeiten und seiner Eigenschaft während der Wachstumsphase CO_2 zu absorbieren und zu speichern von grosser Bedeutung. Insbesondere in Hinblick auf den Verbrauch von Rohstoffen hat das Wachstum von der Entwicklungs- und Schwellenländer einen entscheidenden Einfluss auf die globale Fragen zu Umwelt und die Gesellschaft. Diese Entwicklungen und Veränderungen müssen durch nachhaltige Technologieentwicklung unterstützt werden. Dabei sollte beachtet werden, dass grosse Teile der benannten Regionen in subtropischen Zonen liegen. Technologien zum Einsatz von erneuerbaren Rohstoffen in subtropischen Bedingungen sind daher von zunehmender Bedeutung.

Es ist heutzutage allgemein anerkannt, dass der Bauindustrie sowohl bei Rohstoffverbrauch als auch bei der Urbanisierung von Wirtschaftsregionen eine Schlüsselrolle zukommt. Nachhaltigeren Bauweisen und Bauwerken können einen entscheidenden Einfluss auf die Abmilderung des Klimawandels haben. Insbesondere die Wahl von Bauweise und Baustoffen und die Verbesserung der Energieeffizienz sind von besonderer Bedeutung. Es existiert eine Vielzahl an Studien, die die Energieeffizienz der Bauwerke untersuchen. Zudem sind verschiedenste Technologien bereits seit geraumer Zeit im Einsatz. Der Stand der Technik sind hoch-isolierte und luftdichte Gebäude, mit einer Mischung aus passiven (unter Vermeidung von Energieeinsatz) und aktiven (mit aktiven Energieeinsatz) Massnahmen. Diese Technologien wurden jedoch basierend auf der Erfahrung in vorwiegend kalten und milden Klimaregionen entwickelt.

Mit Blick auf die zuvor beschriebenen Aufgaben und den Anteil des Landes, das durch subtropisches Klima aufweist, hat Japan ein enormes Potential seine Bauindustrie nachhaltiger zu gestalten Dues gilt insbesondere vor dem Hintergrund der Grösse seines Marktes (z.B. 1‘000‘000 neugebaute Häuser im Jahr 2008) und seinem eher rückständigen Energiestandard. Bei der Entwicklung neuer Bauweisen sollten die folgenden Punkte sorgfältig beachtet werden.

In Japan weist aufgrund seiner geographischen Eigenschaften stark unterschiedlichste klimatische Bedingungen auf. Die nördlichen Regionen haben ein kontinentales Klima vergleichbar mit dem in Mittel- und Nordeuropa wohingegen die zentralen und südlichen Regionen ein subtropisches Klima haben. Japan ist in den Gesetzen zum sinnvollen Einsatz von Energie im Bausektor in sechs Klimazonen eingeteilt. Diese klimatische Vielfallt sollte bei der Planung von Bauwerken so gut wie möglich beachtet werden.

Ein weiterer wichtiger Aspekt für Japan ist der Einsatz von Holz aus einheimischen Beständen. Obwohl 93% der freistehenden Häuser aus Holz konstruiert sind (2008) und 66% des Landes bewaldet ist, beträgt die Selbstversorgungsquote nur 26% (2010). Um die Versorgung mit dem Rohstoff Holz sicherzustellen wurde nach dem Zweiten Weltkrieg ein ausgiebiges Aufforstungsprogramm betrieben. Heutzutage stellen diese dichtbepflanzten Wälder aufgrund ihrer verringerten CO2-Speicherfähigkeitun der gesteigerten Gefahr von Erdrutschen ein massives Probleme dar. Parallel befindet sich die einheimische Fortwirtschaft in einer langanhaltenden Rezession durch den Import von niedrigpreisigen Hölzern aus dem Ausland. Für ein nachhaltiges Waldmanagement ist es daher absolut notwendig geeignete profitable Massnahmen zur Ankurbelung der Forstindustrie zu schaffen. Der Schlüssel besteht auch darin unprofitablen Produkten wie dünnen Hölzern einen Mehrwert zu geben.

Die aktuellen Bemühungen der japanischen Bauindustrie konzentrieren sich auf den Einsatz ausländischer Technik im Bereich passiver Energieeffizienz und der bereits hochentwickelten japanischen Haustechnik, wie fortschrittliche Wärmepumpen, Brennstoffzellen und ähnlichem. Die rapide Änderung durch direkten Ersatz heimischer Produkte ohne eine ausreichende Berücksichtigung von lokalen Gegebenheiten und sozio-kulturellen Aspekten resultiert in bauphsikalischen Problemen durch Feuchteschäden und führt zu Problemen in der allgemeinen Akzeptanz solcher Lösungen beim Nutzer. Da die japanische Regierung eine obligatorische Regulierung der Energieeffizienz für alle Gebäude innerhalb des nächsten Jahrzehnts plant, besteht der dringende Bedarf nach Lösungen, die sowohl das subtropische Klima als auch sozio-kulturelle Aspekte entsprechend berücksichtigt. Mit Hinblick auf die erforderliche Verwendung einheimischer Hölzer und die bereits hochentwickelte Haustechnologie kann vor allem eine neuartige Gebäudehülle, die den sinnvollen Einsatz von Rohstoffen und Energien sicherstellt, ein Teil der Lösung sein.

Zur Lösung dieser Aufgaben wurde im Rahmen des Forschungs- und Entwicklungsprojekts, das durch die Kommission für Technologie und Innovation gefördert wird (Förderungsnummer: 9755.1 PFIW-IW), ein dampfdiffusions offenes System einer Gebäudehülle auf Basis von Holzwerkstoffen entwickelt. Die Hülle besteht hauptsächlich aus Lagen natürlicher Materialien, in Form einer äusseren Isolationsschicht aus Holzfaserplatten, einer tragenden Schicht aus Brettsperrholz aus Brettlamellen mit kleinem Querschnitt und einer inneren Schicht bestehend aus einer vorgetrockneten Lehmplatte las Trockenwerkstofft. Jede Komponente besitzt hygroskope Eigenschaften bei einer moderaten Dampfpermeabilität. Das Systemerlaubt einen beidseitigen Feuchtetransport durch die Wand. Die Dicke der einzelnen Schichten kann unabhängig voneinander gewählt werden. Dieses Konzept erlaubt es das Problem von kritischer Feuchtigkeit im Inneren von Aussenwänden unter subtropischen Bedingungen zu lösen. Neben den bauphysikalischen Fragestellungen müssen bei der Planung einer nachhaltigen Gebäudehülle ökologische, ökonomische und sozio-kulturelle Aspekte berücksichtigt werden. Die verwendeten Komponenten bestehen aus natürlichen Materialien und können daher unter Verwendung lokaler Rohstoffe produziert werden. Diese Produktion stärkt die regionale Wirtschaft und erzeugt so Wertschöpfungskette zur Förderung der Forstwirtschaft. Die örtlichen klimatischen und sozio-kulturellen Bedingungen, wie dem Nutzer-verhalten, können durch die anpassungsfähige Struktur der einzelnen Schichten der Gebäudehülle berücksichtigt werden.

In dieser Doktorarbeit wurde das bauphysikalische, ökonomische und ökologische Verhalten des Gebäudehüllensystems unter den japanischen Randbedingungen bewertet. Im Fokus stand es die Möglichkeit der Einführung dieses Systems in den japanischen Markt zu evaluieren. Ebenfalls untersucht wurde die Anwendung der Entscheidungsgrundlagen und Lösungsansätze auf andere Bauweisen und Regionen.

Die Überprüfung des allgemeinen Systemverhaltens wurde innerhalb einer interdisziplinären Zusammenarbeit durchgeführt. Zunächst wurde das hygrothermische Verhalten der Gebäudehülle mithilfe eines Modells zur Simulation instationärer Feuchte- und Wärmeleitung analysiert. Dieses Modell wurde durch Experimente an massstabsgerechten Wandaufbauten überprüft. Im nächsten Schritt wurde ein Modell zur Simulation der Innentemperatur, relativen Luftfeuchtigkeit und der Heiz/Kühllasten erstellt, um das energetische Verhalten eines Gebäudes mit der entwickelten Gebäudehülle zu untersuchen. Dabei wurde der hygrothermische Zustand der Gebäudehülle selbst und des gesamten Gebäudes kombiniert um auf diesem Weg die beidseitige Interaktion der Gebäudehülle zu berücksichtigen. Abschliessend wurde ein Modell zur Bestimmung der ökonomisch und ökologisch optimalen Dicke der Isolierung erstellt. In diesem Ansatz wurde das oben beschriebene Modell der Transmissionswärmeverluste mit Methoden der vereinfachten Lebenszyklusbewertung (Life Cycle Assessment (LCA)) und einer Lebenszykluskostenbewertung (Life Cycle Cost Assessment (LCCA)) verknüpft. Es wurden verschiedene Sensitivitätsszenarien untersucht um die Unsicherheit über die zukünftige wirtschaftliche Situation zu berücksichtigen.

Diese Doktorarbeit ist eine Cumulative Dissertation und besteht aus sechs Kapiteln. Kapitel 1 beschreibt die allgemeinen Hintergründe und das Ziel der Arbeit. In Teil 1.1 wird eine Einführung in das generelle Konzept der Nachhaltigkeit in der technologischen Entwicklung als Orientierungshilfe zu Beginn der Arbeit, sowie eine Einführung in die globalen Herausforderungen für den Bausektor und in Rahmenbedingungen der relevanten subtropischen Regionen gegeben. In Teil 1.2 werden die besonderen Bedingungen der japanischen Bauindustrie und ihre spezifischen Probleme erläutert.In Kapitel 2 wird der Lösungsansatz des Gebäudehüllensystems vorgestellt Abschliessend werden die Methoden zur Bewertung des Systemverhaltens hinsichtlich der Bauphysik, Ökonomie und Ökologie anhand der Begutachtung vorhandener Studien behandelt.

Die folgenden drei Kapitel (3, 4 und 5) bestehen aus drei Forschungsartikeln (Paper I, II und III). Kapitel 3 beinhaltet Paper I, das in einer wissenschaftlichen Fachzeitschrift (peer-reviewed) publiziert wurde (Paper I: Building and Environment - Preliminary Investigation of a Vapor-open Envelope Tailored for Subtropical Climate). Kapitel 4 beinhaltet Paper II, das in einer wissenschaftlichen Fachzeitschrift (peer-reviewed) publiziert wurde (Paper II: Building Simulation - Heat and Moisture Balance Simulation of a Building with Vapor-open Envelope System for Subtropical Regions). Kapitel 5 beinhaltet Paper III , das in einer wissenschaftlichen Fachzeitschrift (peer-reviewed) publiziert wurde (Paper III: Energy and Buildings - Economic, Ecological and Thermo-hygric Optimization of a Vapor-open Envelope for Subtropical Climate).

In Kapitel 3 (Paper I) werden das hygrothermische Verhalten des Gebäudehüllensystems anhand von Versuchen an massgetreuen Wandaufbauten in einer Klimakammer und die zugehörigen eindimensionalen Simulationen des instationären Wärme- und Feuchtedurchgangs vorgestellt. Um die Übereistimmung zwischen Berechnung und Messung zu gewährleisten, wurden die einzelnen Materialien hinsichtlich ihres Feuchte- und Temperaturverhaltens untersucht. Die Ergebnisse in Kapitel 3 zeigen, dass die Versuche und numerischen Simulationen sehr genau übereinstimmen. Basierend auf diesen Ergebnissen wurden Ansätze zur Berechnung des Verhaltens eines Wandaufbaus unter realen klimatischen Bedingungen in Zentraljapan (Kyoto) erarbeitet. Die Ergebnisse zeigen, dass unter korrekter Auslegung des Wandsystems für die realen klimatischen Bedingungen in Kyoto kein Risiko der Kondensation von Feuchte im Wandaufbau und damit verbundenes Schimmelwachstum besteht.

In Kapitel 4 (Paper II) wird das Modell zum Wärme- und Feuchteverhalten eines Gebäudes mit dem Gebäudehüllensystem vorgestellt. In dem entwickelten Modell wurde die Feuchtespeicherung durch die innenseitigen Materialien zusätzlich zu den üblichen Faktoren wie Lufteintrag, Feuchtelast der Innenräume durch menschliche Aktivitäten etc. berücksichtigt. Es wurde versucht eine Vorhersage des Feuchtespeicherungswertes (moisture buffer value (MBV)) der inneren Oberflächenmaterials zu treffen, die durch empirische Daten überprüft wurde. Daraufhin wurde die Gebäudeberechnung unter den Randbedingungen der japanischen Stadt Hikone durchgeführt und der Energieverbrauch und der Beitrag der Feuchtespeicherung auf den Komfort im Innenraum untersucht. Die Ergebnisse des Kapitels 4 können wie folgt zusammengefasst werden: Der MBV von mineralischen Materialien wurde mit hoher Genauigkeit vorhergesagt. Hingegen waren der MBV der holzbasierten Materialien deutlich grösser als die Ergebnisse aus Versuchen. Für eine genauere Vorhersage des MBV sollte für holzbasierte Materialien die nichtlineare Feuchteleitfähigkeit auf Faserebene berücksichtigt werden. Der Heizbedarf für das Versuchshaus betrug 9.4 kWh/m^2, der Kühlbedarf betrug 14.5 kWh/m^2. Die Feuchtespeicherung der verwendeten Materialien resultierte in einer signifikanten Senkung der Feuchteschwankungen. Zusammengefasst kann gesagt werden, dass das Gebäudehüllensystem für hoch energieeffiziente Gebäude unter subtropischen Bedingungen angewendet werden kann. Um sowohl die Energieeffizienz als auch den Innenraumkomfort von Gebäuden in subtropischen Regionen zu verbessern, ist die Entwicklung einer ganzheitlichen Methode zur Bestimmung des optimalen

Gebäudeentwurfs notwendig. Hierbei ist es wichtig die Feuchtespeicherung der Innenraummaterialien als auch allen weiteren relevanten Faktoren wie Verschattung, Entfeuchtungsmassnahmen und weiteren zu berücksichtigen.

In Kapitel 5 (Paper III) wurde die optimale Dicke der Isolation eines Gebäudes mit dem Gebäudehüllensystem unter den Bedingungen in acht Städten in Japan durch Kombination eines ökonomischen und ökologischen Modells unter Berücksichtigung sowohl der Anfangsinvestitionen als auch der laufenden Kosten ermittelt. Grundlegendes Ziel war es die optimale Dicke der Isolation eines Gebäudes unter Abwägung der ökonomischen und ökologischen Aspekte zu bestimmen („ Je dicker die Isolation, desto weniger Heizenergie aber desto mehr Material wird verbraucht"). Die zur Gewährleistung der Dauerhaftigkeit des Gebäudes notwendige minimale thermo-hygrische Dicke wurde ebenfalls bestimmt. Das in dieser Simulation verwendete Modell für die Transmissionswärmeverluste basierte auf dem in Kapitel 4 vorgestellten Gebäudemodell. Die folgenden Erkenntnisse konnten gewonnen werden: 1) die ökologisch optimale Dicke ist grösser als die ökonomisch optimale Dicke, 2) das hygro-thermische Minimum lag in einem Grossteil der Fälle innerhalb des ökonomisch optimalen Bereichs und 3) der Zinssatz der Währung und der Anstieg des Strompreises haben einen entscheidenden Einfluss auf das Ergebnis des Optimierungsprozesses. Mit Hilfe des Optimierungsmodells konnte gezeigt werden, dass die Anwendung des Gebäudehüllensystems für Japan ökologisch und ökonomisch sinnvoll ist, insbesondere in den mittleren und südlichen Regionen.

Abschliessend werden in Kapitel 6 die Ergebnisse und Erörterungen der Kapitel 3-5 zusammengefasst und diskutiert. Die wichtigsten Schlussfolgerungen sind:

- Das hygrothermische Verhalten des Gebäudehüllensystems wurde erfolgreich modelliert und überprüft.
- Mit Hilfe des vorgeschlagenen Modells zum Wärme- und Feuchtegleichgewicht war es möglich die Innenraumtemperatur, die relative Feuchte und den Heiz/Kühlbedarf vorherzusagen und die Eignung des Gebäudehüllensystem für das realisieren von hoch energieeffizienten Gebäuden unter subtropischen Bedingungen zu verifizieren.
- Mit Hilfe des vorgeschlagenen Optimierungsmodells für die Isolation konnte gezeigt werden, dass die Einführung des Gebäudehüllensystems in Japan ökologisch und ökonomisch sinnvoll ist, insbesondere in den mittleren und südlichen Regionen.

Es verbleiben verschiedenen Defizite in den Modellen, die nachfolgend behoben werden sollten. Dies betrifft das Verhalten des hygrothermischen Modells bei Schlagregen, das begrenzten Volumen in der Gebäudesimulation und die begrenzte Anzahl an Parametern im Optimierungsmodell bezüglich lokaler Randbedingungen (Materialpreis, Energiemix, etc.). Es wird eine hohes Potenzial gesehen das allgemeine Modell durch eine Optimierung der

Isolationsdicke und der Haustechnik zum Ausgleich zwischen Energieverbrauch und Komfort im Innenraum zu erweitern und Aussagen so breiter abzustützen.

Es kann zusammengefasst werden, dass das in dieser Arbeit vorgeschlagene Gebäudehüllensystem ein grosses Potenzial für die Einführung in Zentraljapan hat, um einen Beitrag zu erhöhter Nachhaltigkeit der japanischen Bauindustrie leisten. Dies gilt ebenso für andere Regionen mit ähnlichen klimatischen Bedingungen. Die Methoden der Modellierung (das hygrothermische Gebäudemodell und das Optimierungsmodell für die Dicke der Isolation) können zukünftig mit geringen Anpassungen auch auf andere Bauweisen übertragen werden. Das hygrothermische Gebäudemodell wird in Zukunft durch empirische Daten aus einem Versuchshaus validiert werden (voraussichtliche Fertigstellung in Ohmihachiman in Mai 2013).

要約　(Summary in Japanese)

地球温暖化問題の顕在化と今後の更なる進展の可能性が高い現状にあたって、気候変動の緩和は緊急の問題である。人間社会の今後の更なる発展が望まれるとするのならば、技術開発のありようはサステナブルであることを基本としなければならない。新たに開発される技術について、その生産・運用のプロセスは、同時代の、そして未来の世代の平等な発展の機会を損なうものであってはならない。

このような人類共通の理解の中、主に取り組むべき課題は資源の枯渇と新興地域の急激な発展の二点である。資源の有効活用について、活発な議論が今日まで行われ来てはいるものの、現状では再生可能資源の有効活用は十分になされているとはいえない。再生可能資源のなかでは、その材料の汎用性とCO_2の吸収・貯蔵機能ゆえ、木材は重要な材料と言える。資源枯渇の問題と大いに関係して、新興地域の急速な発展が自然環境および人類社会に地球規模で大きな影響を与えている。このような地域のこれからの発展はサステナブルな方策・技術を基になされなければならない。重要なのは、振興地域の多くは亜熱帯性の気候を持つ地域に位置していることが多い点である。すなわち、亜熱帯性の気候に適した解決策をもって問題に取り組むことが肝要といえる。

建設産業は上記の問題の上で重要な役割を果たしており、より合理的な建設活動と建設物の運用により気候変動の緩和に大きく貢献することが期待されている。建設活動そのものには様々な側面があるが、中でも使用される材料および工法の選択、そして運用期間内におけるエネルギー効率が要点である。建物の省エネルギー性については、様々な研究がこれまで行われており既に実用化されている技術も多い。最新の技術は建物の高断熱・高気密化であり、パッシブデザイン（エネルギーの消費を伴わない建物内気候の制御）とアクティブデザイン（エネルギーを消費する建物内気候の制御）の両方をあわせた手法による建物の設計が主流である。このような技術は主に寒冷地域において開発された技術が基本となっている。

上述の問題を背景にして、温暖湿潤性の気候を持つ日本の建設産業は、その規模（2008年でおよそ100万戸の新築住宅）と世界的に見てやや遅れている省エネルギー基準ゆえ、改善の余地が大いにあるといえるが、新たな工法を開発するにあたり、以下の点を十分に考慮に入れなければならない。

日本はその地理的特性を理由に非常に多様な気候を持っている。大陸性気候を持つ北部地域は中央・北ヨーロッパと同様の気候特性を示す一方、中部および南部は温暖湿潤性（亜熱帯性）の気候を有する。その国土はエネルギー使用の合理化に関する法律において六つの気候区域に区分されている。この様な気候の多様性は建物の設計の際には可能な限り考慮をされるべきである。

もう一つの重要な問題は国内の森林資源の利活用である。国内の戸建て住宅市場のストックの実に93%が木造であり、また国土の66%を森林で覆われているのにも関わらず、木材の自給率は2010年の時点で26％にとどまっている。第二次大戦後の木材供給の確保のために過密に植林された森林が、今日では自然環境に悪影響を与えつつある。例えばCO_2の吸収能の低下や土砂災害の危険性の上昇が例として挙げられる。これと同時に林業経済は低価格の輸入材の影響を受け長期間にわたる不況となっている。将来にわたって持続可能な森林・林業経営を行うためには、収益性のある事業により林業経済に刺激を与えることが極めて重要である。要点は間伐材・羽柄材等の小径の木材にさえも利用価値を与えることである。

日本の住宅産業での近年の技術革新は、外国で開発された（主に省エネルギーに関する）技術の移植・応用と自国内での高性能なヒートポンプや燃料電池といった住宅設備の活用に代表される。外国技術の応用に関しては、日本独自の環境的条件を十分に考慮にいれない性急かつ直接的な技術の運用により建築環境工学上あるいは技術の消費者からの支持についての問題が生じている。日本政府が今後十年程度のうちに住宅の省エネルギー基準の適合を義務化することを計画していることもあり、温暖湿潤性の気候と人々の住まい方の両方を考慮した住宅技術の開発が強く望まれる。国産木材の利用と既存の高性能の住宅設備の応用を考えると、資源の有効活用と建物のエネルギー効率を十分に加味した木造の建築外皮（envelope）の開発は有効な手段といえる。

このような背景を受け、水蒸気の透過性のある（以下水蒸気に対して「オープン」と表現する）木造の建築外皮のシステムの研究開発がスイス連邦のCommission for Technology and Innovationの助成により行われた（grant number: 9755.1 PFIW-IW）。当建築外皮は木材繊維による外断熱層、小径の板で構成されるクロスラミナの木質構造パネル、木材繊維と土の複合材料による室内側の仕上げにより構成される。それぞれの部材が自然素材由来で、適度な透湿性と吸放湿性を有する材料である。従って水蒸気は壁内を双方向へ移動することができる。また、それぞれの層の厚さは他の層からは独立して任意の厚さを与えることが出来る。これらの設計上の特性により温暖湿潤性の気候下においての外壁内の水分の蓄積の問題を解決することができる。これらの建築物理学上の考慮の他、経済的、環境的そして社会的な側面についても配慮されている。各部材はごく一般的な自然素材由来であるため、日本各地の地場産の材料による生産の可能性がある。地域内の材料の供給および生産は地域経済に貢献しうる。また、日本各地の多様な気候特性と住まい手のライフスタイルを加味して外皮の構成を柔軟に変えることが出来る。

本論文ではこの建築外皮システムの建築物理的、経済的そして環境的性能の定量的評価を行った。限定的な目的としては当建築外皮システムの日本の市場での活用の可能性の評価であるが、同時に当論文において提案される評価手法自体は他の工法あるいは他の地域への応用を念頭においたものである。

当建築外皮システムの性能評価は学際的な手法により行った。まず、外皮の耐久性の検証のために、このシステムを用いた壁構造の温湿度に関わる性能を1次元の非定常水熱同時移動モデルを用いて分析した。このモデルは実大の壁試験体を用いた実験によりその精度

を検討した。さらに、当建築外皮を用いた建物全体のエネルギー性能の検証のために、建物内の気温、相対湿度および冷暖房負荷を予測するモデルを上述の外皮の温湿度性能モデル、建物全体の熱収支そして壁の吸放湿性能まで考慮した居室の水分収支モデルにより構築した。そして、日本の各種条件下での適用可能性の検証のために、経済性および環境性の両方を加味した最適な断熱層の厚さを求める最適化モデルを、上述の建物全体の熱水分収支モデルおよび簡易なライフサイクルアセスメント、ライフサイクルコストアセスメントのモデルにより構築した。この最適化モデルにおいては将来予測の不確実性を考慮し複数のシナリオが用いられた。

本論分は六つの章から成る。第1章（Chapter 1）は本研究の総合的な背景について述べる。第1.1節（section 1.1）では本研究の技術開発の方向付けとして、技術開発におけるサステナビリティの一般的概念について述べた後、地球規模で見た建設産業と亜熱帯地域における急速な経済発展について概観する。第1.2節（section 1.2）では日本の住宅産業について詳述し、問題提起を行う。第2章では、本研究の目的として、当建築外皮システムの設計思想を詳述した後、既往の研究の概観を含めながらその建築物理的、経済的そして環境的性能の定量的評価手法を示す。

続く3つの章（Chapter 3,4 および5）は3つの研究論文（Paper I, II およびIII）により構成される。第3章（Chapter 3）では査読付き学術誌にて出版された論文（*Building and Environment - Preliminary Investigation of a Vapor-open Envelope Tailored for Subtropical climate*）により成る。第4章（Chapter 4）では査読付き学術誌にて出版された論文（*Building Simulation - Heat and Moisture Balance Simulation of a Building with Vapor-open Envelope System for Subtropical Regions*）により成る。第5章（Chapter 5）では査読付き学術誌にて出版された論文（*Energy and Buildings - Economic, Ecological and Thermo-hygric Optimization of a Vapor-open Envelope for Subtropical Climates*）により成る。

第3章（Chapter 3）（Paper I）では当建築外皮システムによる壁の温湿度に対する応答性能について、実大の壁試験体を用いた実験およびそれに即した1次元の非定常水熱同時移動モデルによって検証を行った。より精度の高いシミュレーションを行うために、壁を構成する部材それぞれの熱と水分に関する材料物性の測定を行った。結果、測定値と計算値は高い精度で符合し、このモデルの有効性が確認された。この結果に基づき、日本の実際の気候条件下での壁の温湿度挙動を検証するために、京都市の気象観測データを用いてシミュレーションを行い、この条件下で外壁内の結露およびカビの発生のリスクを避けることが可能であることが示された。

第4章（Chapter 4）（Paper II）では当建築外皮システムを用いた建物の熱水分収支モデルを提案した。水分収支モデルにおいては、外気の流入や室内の人間活動といった一般的な要素に加え、室内内装材による吸放湿も考慮に入れられた。内装材の吸放湿特性値（Moisture Buffer Value, MBV）の予測が試みられ、実験値との比較が行われた。続いて、建物全体の熱水分収支のシミュレーションを彦根市の気候条件を基に行い、建物のエネルギー消費および吸放湿の快適性への影響を検証した。結果は以下の通りである。まず、鉱

物系の内装材のMBVは高精度で予測された。しかし、木質系材料のMBV予測値は測定値よりも大幅に高い値が得られた。木質系材料のより正確なMBVを予測するためには、吸放湿の木繊維レベルの非線形伝導性を考慮に入れたモデルの作成が必要である。建物全体の暖房および冷房負荷はそれぞれ9.4 kWh/m^2 、14.5 kWh/m^2であった。内装材の吸放湿により、室内の湿度の変動が大幅に低減された。従って当建築外皮を用いた建物により、高い省エネルギー性能を持つ建物を温暖湿潤地域において達成できることが示された。温暖湿潤地域の建物の省エネルギー性と快適性の両方をより高めるためには、内装材による吸放湿のみではなく、日射遮蔽や除湿などを含めたより総合的な最適な手法の開発が必要である。

第5章（Chapter 5）（Paper III）では当建築外皮システムを用いた建物について、日本内の八都市の条件下、初期投資およびランニングコストの両方を考慮に入れた経済性および環境性の定量化モデルのよりその断熱層の最適な厚さを検証した。その意図の根底は最適な断熱厚さの定義において経済性と環境性の二律背反（「断熱層を熱くすると、暖房負荷は下がるが材料の使用量は増える」）を考慮する点にある。水分によるダメージを避け、建物の寿命を保証するためにも熱水分に関わる最低限の断熱厚さも定義した。これらのモデル内の建物の熱損失モデルには第4章（Chapter 4）で提案した建物全体の熱水分収支モデルが適用された。得られた主な結果は以下の通りである。（1）環境的最適厚さはすべてのケースにおいて経済的最適厚さを上回った、（2）熱水分に関わる最低厚さはほとんどのケースにおいて経済的最適厚さの範囲内であった、（3）通貨の利率と電気料金は最適化モデルによる解析結果に大きな影響を与える。提案された最適化モデルを用いて、当建築外皮システムを用いた建物の中部および南部日本における適用性の高さが示された。

最後に、第6章（Chapter 6）において第3-5章での結果と考察をまとめ、総括的結論が示される。主な結論は以下の通りである。

- 当建築外皮システムの温湿度への応答のモデル化が行われ、その有効性が示された。
- 本研究で提案された熱水分収支モデルを用いて、当建築外皮システムを用いた建物の室内気温、湿度および冷暖房負荷を予測することができ、温暖湿潤気候下において高い省エネルギー性を達成することが出来ることが示された。
- 本研究で提案された断熱厚さ最適化モデルを用いて、当建築外皮システムを用いた建物の中部および南部日本における適用性の高さが示された。

各モデル内の改善が必要な主な点として、温湿度応答モデル内の液水移動特性、全建物の熱水分収支モデルの空間ボリュームの節点数の制限、断熱厚さ最適化モデルの地域特性に関する変数（材料の費用、エネルギーミックス等）の制限が挙げられる。また、モデル全体の拡張可能性として、エネルギー消費と室内の快適性の二律背反を加味した断熱厚さと建築設備の最適化モデルの追加が挙げられる。

以上より、本研究により提案された建築外皮システムの、日本の住宅産業のサステナビリティを増進するために活用されるポテンシャルの高さが示された。この建築外皮システム

は同様の気候特性を持つ別の地域においても活用することが出来る。また、システム全体の評価手法（全建物の熱水分収支モデルおよび断熱厚さの最適化モデル）は軽微なモデルの変更をもって他の工法システムへも応用することができる。全建物の熱水分収支モデルは滋賀県近江八幡市に建てられる実験住宅（2013年5月竣工予定）での温湿度測定によりその精度が検証されることになっている。

1 Introduction

1.1 Sustainability of the construction industry

1.1.1 Sustainability and technology development

In light of the high probability of global warming, the mitigation of climate change is one of the most urgent issues of our time. It has been reported that the average air temperature had risen by at least 0.5°C by 2000 because of anthropogenic greenhouse gasses (GHG) emissions (Wigley 2005). The temperature increase is projected to accelerate due to extensive GHG emissions in the last decades, and it would have a significant impact on water resources, ecosystem, food supply, human health and so on (Intergovernmental Panel on Climate Change (IPCC) 2007). There is a substantial need to deal with this issue.

However, the ambiguity of how GHG emissions contribute to climate change makes the definition of responsibility of human activities related to GHG emissions very intricate. The reason is that the influence of human activities to climate change is not tangible due to the spatial and temporal dispersion of causes and effects (Gardiner 2006). The active GHG emissions by rich countries might cause catastrophic consequences in poor countries, but this would not be direct and visible damage to the major polluters. Also the temperature increase that the current generation is facing is actually being induced by the past activities of humans, and obviously the emissions by the current generation would cause the suffering of future generations. The inertia of the nature in terms of the reaction to GHG emission makes evaluating the responsibility of each generation's activities very complex.

Here lies the importance of the fundamental philosophy of sustainability. As long as human society continues growing, no human activities should deteriorate the equal opportunities of people to continue to grow through time and space. The sacrifice of people's right in the same generation and the backload to future generations must be minimized as much as possible.

The idea of sustainability holds true in any kind of human activity, and technology development is no exception. Then a question arises: "What is sustainability in technology development?" or in other words, "How sustainably should technologies be developed?" According to Elkington, sustainability consists of three pillars: ecological, economic and social pillars (Elkington 1998). The preservation of the ecosystem is implicated in Ecological sustainability. As addressed above, climate change mitigation is one of the biggest issues of our time, so technology development should contribute to this issue by reducing the amount of GHG emissions. The profitability and affordability of technologies is implicated in economic sustainability. A wide range of items, such as human rights, human health and so on, are implicated in social sustainability. When related to technology development, its primary concern is social acceptance, namely whether or not the technology is accepted by the society to which it is introduced.

The most important process in technology development is designing. The design of a product defines the product's functionality and its degree of sustainability (hereafter called "sustainability performance"). There is a difference between the fulfillments of functionality and sustainability performance. Fulfilling its functionality is the end of the product ("an HVAC (heating, ventilating and air conditioning) unit creates comfortable indoor climate.") Meanwhile, fulfilling its sustainability performance is the measure of how sustainably the functionality of the product is achieved ("an Energy efficient HVAC unit contributes to the reduction of GHG emission and lower electricity expenses without deteriorating the indoor comfort.")

The value of functionality is determined in several ways. Friedman et al. define three types of value determination: embodied, exogenous and interactional (Friedman et al. 2003). Embodied determination is the value determination introduced by designers. The design of a product informs how users use it. Many hardware (for example communication equipment such as telephone) and social infrastructure are typical products. Exogenous determination is the value determination given by users. The personal computer is a good example of this. Users have developed a vast number of software and programs in order to utilize the functionality of computers, which is merely based on a binary numeral system and a certain amount of memory storage. The important point is that the exogenously determined value is very much dependent on the social context. ("Who are the users?", "where is it used?", "what are the infrastructures available?" and so on.) The interactional determination is the value determination given by both designers and users. Product improvements based on the interactive communication between designers (producers) and users may be a process of this determination.

Now, by which type of value determination should the sustainability performance value of a product be determined? Regarding ecological sustainability performance, the fundamental difficulty lies in the spatial and temporal dispersion of causes and effects as mentioned above. It is very likely that if the negative effect resulting from a certain activity is not really visible or tangible, people tend to behave selfishly so that the individual benefit would be maximized at the cost of invisible pollution (referred to the concept of "Tragedy of Commons" (Hardin 1968)). Therefore ecological sustainability performance should not be determined by the users' behavior (exogenous determination) but on the performance of the product itself (embodied determination). This means that products whose performance is not basically altered by users should be designed so that they have as little of environmental impact as possible, not only in the production process but also in the use phase regardless of how users use them. Regarding economic sustainability performance, the cost of producing and using products should be affordable both for producers and users. A general way of marketing should apply to product development as long as there is no external means to stimulate the market (for example governmental subsidies). This may be characterized by interactional determination because price setting is the consequence of balancing between supply and demand (producers and users). Regarding social sustainability performance, the acceptance by users is key as discussed above. Therefore the value determination should be exogenous. This means that the adaptability to local requirements according to the social context should be inherent in the design of technologies.

Therefore the discipline of sustainability in technology development can be formulated as follows: emerging technologies should ensure a low environmental impact by its design, should be affordable and should be adaptable to local conditions. When those values conflict with each other, the optimization dealing with the trade-off should be thoroughly considered.

1.1.2 Global issues

With regard to climate change mitigation, the major issues are resource depletion and the rapid urbanization of developing regions.

Resource consumption is divided into two main utility forms, energy use and material use. As for energy use, the main resource of energy consumption to produce electricity since Industrial Revolution has been non-renewable fossil fuel, such as petroleum and coal. In order to reduce the ecological impact of electricity production and use, renewable power production (hydropower, solar, wind, biomass, geothermal and ocean) has been promoted in recent years. However, even though the progress of, for example, solar PV (photovoltaic) is rather successful (40% increase from 2000 to 2011), the utilization of renewable energy is still limited to a certain extent (about 3% of total electricity production) (International Energy Agency (IEA) 2012). The major challenge is determining whether to ensure energy security and economy or to further promote the climate change mitigation. As for the material use of resources, wood has become of high importance because of its diverse usages and its nature of absorbing and storing CO_2. Wood has a wide range of usages such as building components, biomass fuel and raw materials for the chemical industry. In order to further effectively use wood resources, research and development has been strongly promoted worldwide. For example in Europe, the Forest-Based Sector Technology Platform (FTP) was established in 2004 (FTP 2005). For the sake of obtaining an economic and environmental balance in using wood and eventually helping society to mitigate climate change, FTP has published “Strategic Research Agenda” (FTP 2006) for formulating its 5 research objectives and 23 research areas. By 2011, 13 European countries have adopted this agenda and published their own national agendas, and active research is now beginning (for example Swiss National Research Program 66 “Resource Wood” (Swiss National Science Foundation 2010)).

Much related to the issue of resource consumption, the rapid urbanization of developing regions has a significant impact on the environment and human society. In the second half of the 20th century, the global population more than doubled and this growth happened mostly in developing regions (CIB & UNEP-IETC 2002). According to the United Nation’s definition of megacity (which has the population of more than 10 million), there are 19 megacities in the world (United

Nations 2007), and most of them are located in developing countries (see Figure 1-1). Those areas are facing a number of problems, such as insufficient infrastructure, low-quality housing, dense population, a low level of hygiene and so on. Such backward development puts those regions in very difficult situations, but it also means that future development could be more effective, reflecting on the lessons learned in developed regions. Therefore the introduction of sustainable technologies (mainly in the construction sector) to these developing regions is urgently needed (CIB & UNEP-IETC 2002). It should be noted that a large part of such emerging economies are situated in subtropical regions. Figure 1-1 shows the subtropical regions defined by Köppen-Geiger climate classification (Cwa and Cfa), including regions with an extreme difference between hot and humid summer conditions and very cold and dry winter conditions (humid continental climate, Dwa). Interestingly, the major (economic-wise) emerging countries (China, India and Brazil) have wide areas with those climatic conditions. Moreover, some developed countries also have the same climatic conditions in areas that are rather highly populated (the southeast part of the United States, the east coast of Australia and the majority of Japan). This indicates that technology development that takes use in a subtropical climate into account is key in order to contribute to the creation of a more sustainable society.

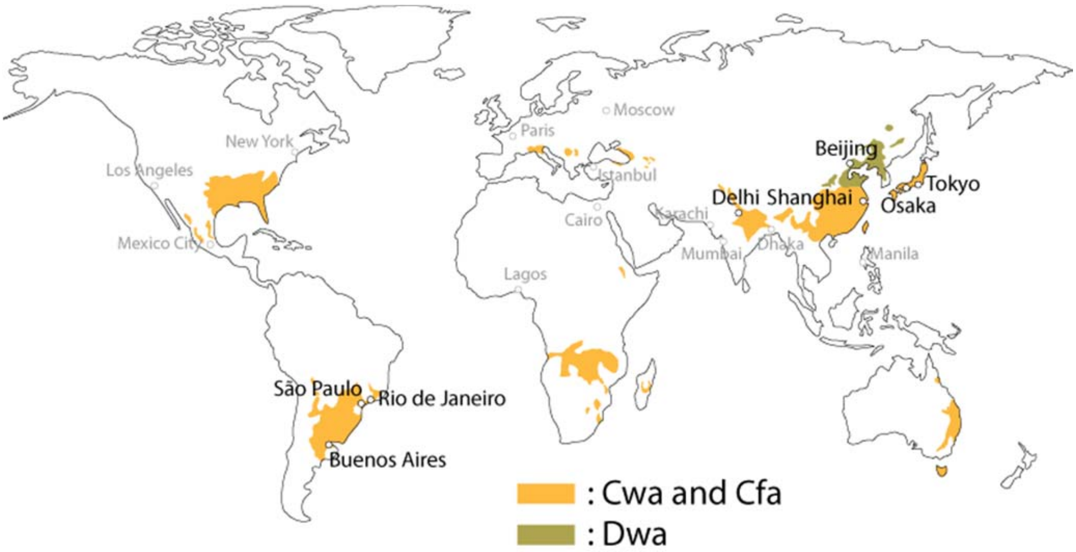


Figure 1-1: The subtropical regions and megacities in the world

1.1.3 Sustainability in the construction industry

Today it is widely recognized that the construction industry plays a key role in the global issues addressed above. On a global scale, the construction industry contributes to about 50% of manmade greenhouse gas emissions and to about 40% of the resource consumption (UNEP 2003). Also, the energy demand from the construction sector is projected to double by 2050 due to the expanding global population (IEA 2012). Rational management of construction activities and usage of buildings may have a significant impact on climate change mitigation. The selection of construction method/materials and the implementation of energy efficiency measures are key points to be considered.

Regarding energy efficiency, there have been a number of studies in European countries. After the oil shock in the 1970's, a concern for the rational use of energy emerged in order to realize a society that is less dependent on fossil fuels, especially petroleum. Due to the large amount of energy consumption for heating in winter, northern European countries put regulations on energy efficiency of buildings into effect (for example (Svensk Byggnorm (Swedish Building Regulations) SBN 75 1975). This effort was actually rather concerned about the economic aspect: the principle was that the energy supply was secured and the economy should further develop with less oil consumption. After the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, the general perspective on environmental affairs changed greatly. The viewpoint on how to deal with the environmental issues has changed from that of local and limited measures to more holistic measures on a global scale, namely from the regional visible pollution issue to the global warming issue. Accordingly, regulation on the energy efficiency of buildings has become important in the ecological aspect as well since then. Today all OECD member countries and many others have their own building energy code and some of them (EU countries, China and Tunisia) have made them mandatory on the national level (IEA 2012).

State-of-art energy efficient building technology is super-insulated and airtight buildings, which are often a hybrid of passive and active measures. Active measures are performed by building equipment such as an HVAC unit involving active energy consumption. This is a measure to create desirable room conditions in terms of comfort and health. The efficiency of such a device is key. In contrast, passive measures are performed by natural physics such as natural ventilation (wind by air pressure difference) and solar gain (heat by solar radiation). These are measures to reduce heating/cooling demand. In this case adapting building design (window size, orientation and so on) to the geographic and climatic condition of the building site is key. In terms of energy efficiency, the ideal approach to building design then is firstly to enhance the passive measures in order to minimize the heating/cooling demand, and secondly to employ energy efficient active measures, if necessary, for regulating the indoor climate within comfort range.

The standardization of energy efficient building technology is an effective way of sharing know-how and popularizing the technology. Several standards that require even stricter requirements than above mentioned building energy codes actually exist. For example the MINERGIE®

Building Association of Switzerland has proposed energy certifications such as MINERGIE® and MINERGIE-P®. With the aid of subsidies from local governments in Switzerland, more than 14,000 housings have been voluntarily certified (Beyeler et al. 2009). Passivhaus Institut of Germany also has an energy labeling method for buildings. A recent study has shown that in practical use the average energy performance of certified Passivhaus buildings match the calculated energy demand (Passivhaus Institut 2010). This proves that the implementation of such advanced standards and labeling systems can contribute to further enhancement of the sustainability of the construction industry.

Other than the energy efficiency issue, the more general way of evaluating buildings from another more holistic sustainability viewpoint is also emerging. A variety of evaluation tools have been developed and implemented for certifying and labeling building (for example BREEAM (Dickie et al. 2000) of United Kingdom, LEED (Cidell 2009) of the United States and CASBEE (Murakami et al. 2004) of Japan). The evaluation method and items evaluated differ from one tool to another, and these items include not only energy efficiency but also social aspects, such as indoor environmental quality, health and well-being, etc. (Reed et al. 2009). Labeling is expected to give incentives to customers for realizing sustainable buildings by, for example, subsidies ensured by the certification.

For these situations, IEA has formulated policies and measures in order to enhance the efficiency of buildings and scale-up the deployment of energy efficient buildings (IEA 2011) as follows:

- Mandatory building energy codes and minimum energy performance that aim to minimize life-cycle cost should be implemented.
- The development and deployment of buildings with net-zero energy consumption.
- The energy efficiency of existing buildings needs to be improved.
- The use of building energy labels or certificates should be promoted in order to provide information to owners, buyers and renters.
- The energy performance of building equipment should be improved.

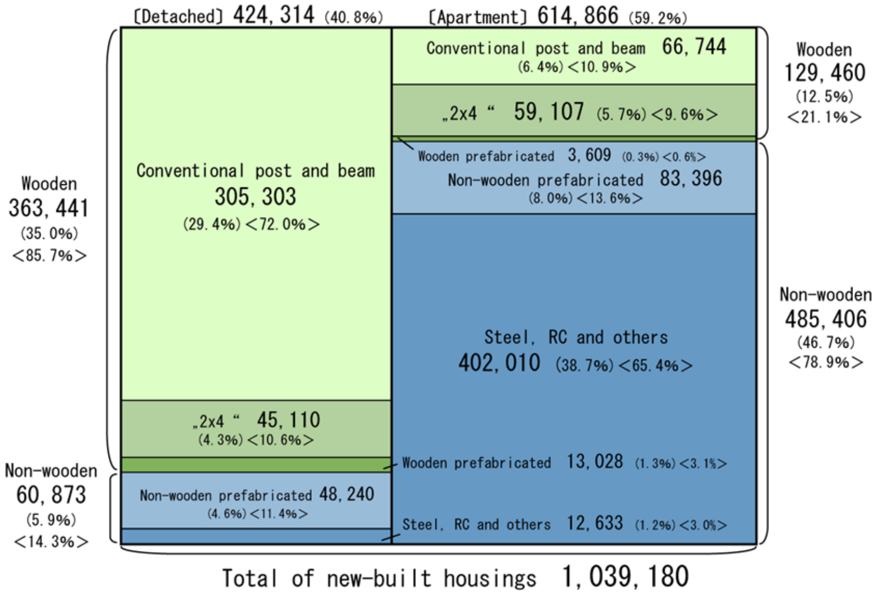
These are the common action assignments worldwide.

1.2 The Japanese wooden housing industry

1.2.1 Overview of the Japanese housing industry

1.2.1.1 General statistics

The market for the Japanese housing industry is considerably big. From the 1960's to the middle of the 2000's, over 1 000 000 new housing units (including both detached houses and individual apartments) were constructed every year. Since the global economy has been in recession, the number of annual newly built house has dropped to around 800 000 (Ministry of Land, Infrastructure, Transport and Tourism (MLIT) 2011a). In 2008, 47% of the total newly built housing units and 86% of the newly built detached housing units were wooden constructions. Figure 1-2 shows the detail of the statistics. Looking at the overall housing stock statistics of 2008 (Ministry of Internal Affairs and Communication (MIAC) 2008), the total number of housing units was around 49 000 000, and 59% of the total housing stock and 93% of the detached housing units were wooden constructions. Wooden construction has the largest share and therefore is the most important building type in the Japanese housing industry.



* Numbers in ( ) express the percentage in the total number.
Numbers in <> express the percentabe in either 〔detached〕 or 〔Apertment〕.

(Source: Housing and land survey 2008, Ministry of Internal Affairs and Communication)

Figure 1-2: Statistics of new-built housings in 2008

Figure 1-3 shows the share of construction method and the size of constructors of newly built wooden detached houses in 2003. The conventional post and beam method accounts for 73.6% of these constructions (see 1.2.1.2). Interestingly, almost 60% of the houses with this construction method were produced by small companies, which produce less than 50 houses per year. This shows that the Japanese housing industry consists of a considerably large number of constructors.

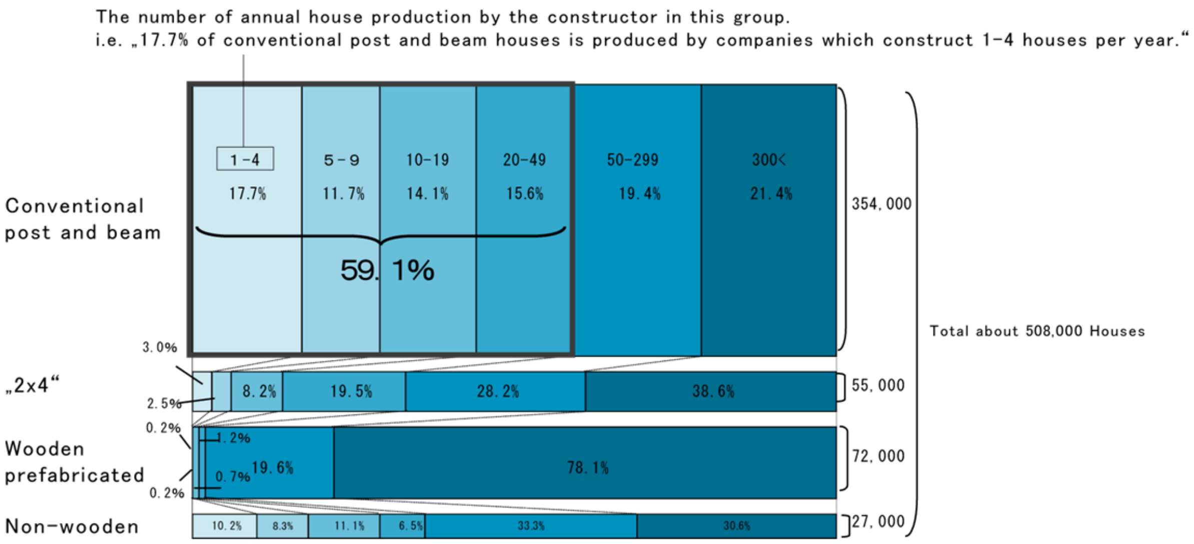
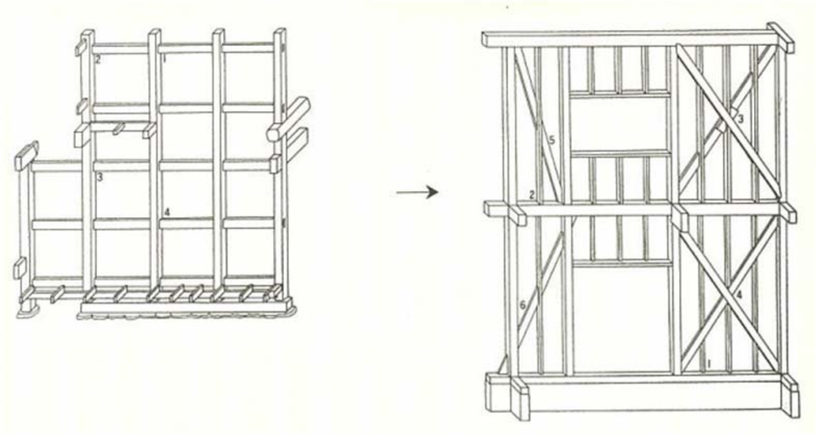


Figure 1-3: Share of each construction method and the size of constructors of new-built wooden detached houses in 2003

1.2.1.2 Conventional post and beam construction

As mentioned in 1.2.1.1, the most common construction type in the Japanese housing industry is the conventional post and beam method. In this section its history is briefly reviewed.

The history of the conventional post and beam construction method, in terms of technology development, cannot be explained without introducing major earthquakes and the eventual revisions of the building code. Japan experienced a huge disaster, the Great Kanto Earthquake, in 1923 around the Tokyo area. More than 100 000 people were crushed or burnt to death by the debris from collapsed wooden buildings. This caused the Japanese government to revise the building code (urban planning law, enacted in 1919) on earthquake safety for the first time. The most important revision was the introduction of a regulation on bracing, which was based not on the traditional Japanese construction but rather on a western engineered approach. Figure 1-4 shows the change from traditional shear reinforcement (*nuki* in Japanese) to wooden bracing.



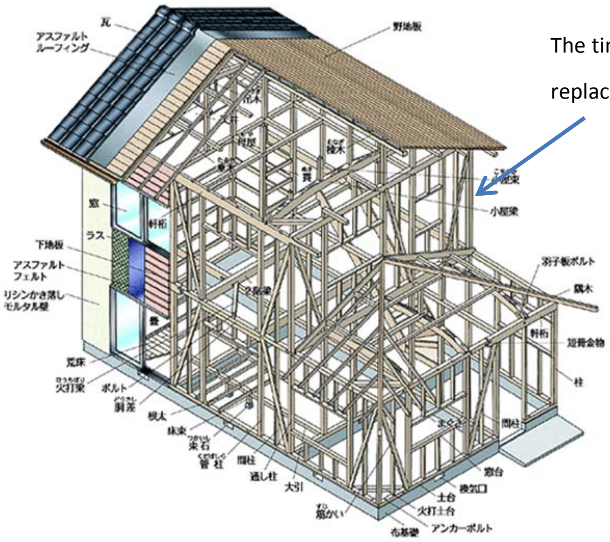
(Picture source: (Matsumura 1999))

Figure 1-4: Change of shear reinforcement technique from traditional to engineered one

This change was followed by the enactment of the building standard law and the establishment of the Housing Loan Corporation (HLC, reorganized into Japan Housing Finance Agency in 2007) in 1950, which were the most important milestones in the history of the Japanese housing industry (Matsumura 1999). Through this law and the specification document on building design published by HLC (HLC 1951), the sound standardization of building design led by the government began. The specification document has been revised annually and is still an important design reference in the current housing industry.

In the meantime, the JAS (Japanese Agricultural Standard) on veneer lumber and plywood products was formulated in 1953. Plywood itself was introduced in Japan in the beginning of 20th century and domestic production has slowly developed. As the use of plywood grew and as foreign construction methods, such as the 2x4 system of North America was introduced in the 1970's, timber bracing has been replaced by plywood in conventional construction. The revision of the building code in 1981 in reaction to the Miyagiken-oki Earthquake in 1978 was an especially significant turning point. Within this revision, the use of plywood as a structural element was integrated into the so-called wall quantity calculation, which is a simplified method for assessing the shear resistance of buildings based on the length and weighting factor of a variety of structural walls.

This change has brought tremendous influence in the construction industry. The use of plywood was further accelerated and it became one of the vital building materials because of its high reliability regarding structural performance and less labor required at the construction site compared to timber bracing. Nowadays, not only the reinforcement of walls is accomplished through plywood but also that of the floor. Consequently the conventional post and beam construction method has become a mix of post and beam construction and frame construction (Figure 1-5).



The timber bracing is often replaced by plywood plating

(Picture source: http://www.sanpookenchiku.com/)

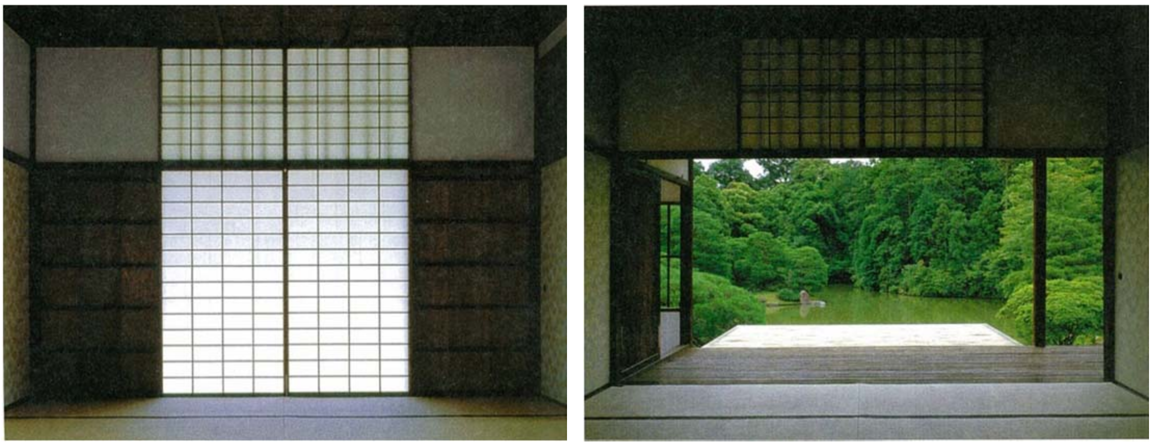
Figure 1-5: Conventional post and beam construction method of Japan

1.2.1.3 Building physics technology

Kenko Yoshida wrote consist of essays "*Tsurezuregusa* (Essays in Idleness)" in the early 14th century. There is a widely known part of this book: "*Ie no tsukuriyou ha natsu wo mune to su beshi. Fuyu ha ikanaru tokoro ni mo suma ru. Atsuki koro waroki sumai ha, tae gataki koto nari.* (The design of housing should be concerned primarily with summer conditions. It is rather easy to live under winter conditions by whatever means. People cannot tolerate the damp heat inside defective houses in summer.)". This concept has prevailed over centuries. Buildings have indeed been constructed with a timber post and beam system so that they have plenty of cross ventilation. The gaps between pillars were either left open with movable partition walls or sliding doors made of paper and wood or permanently closed with mud wall (Figure 1-6). This had been the major construction method of most residential buildings in Japan up until the Second World War.

Following the reconstruction period after the war, the issue of comfort became the demand of inhabitants. Thermal insulation in northern regions was especially a priority along with a concern for energy efficiency due to the oil shock in the 1970's. Local contractors attempted various methods for insulating buildings, and consequently the methods were followed by the first major building physics problem, interstitial condensation in winter.

Imperfect consideration of building detail caused moisture accumulation in the external walls and foundation, and this resulted in the growth of the mold *Serpula lacrymance,* which causes severe structural damage by deteriorating wooden elements ((Nunomura 1979) and (Kamiyama 1982)). Extensive investigations were carried out, and it was revealed that the infiltration of warm room air towards the exterior thorough gaps between building elements was the cause of the moisture accumulation ((Fukushima 1997) and (Kamata et al. 1999)). In these studies, it was shown that the infiltration was due to a lack of consideration of the airflow through the structural elements of the conventional post and beam construction, and it was causing not only the growth of mold but also very inefficient heating. As this type of infiltration is a common problem regarding condensation and the efficiency of heating all over Japan (Mukai et al. 2008), several detail solutions were proposed by private associations and are applied nowadays (for example Shin-mokuzoujutakugijutsu Kenkyukyougikai 2002).



(Photo source: Nakagawa, T. (2002): Nihon no Ie (Houses of Japan). TOTO Publishing, Tokyo.)

Figure 1-6: Traditional Japanese wooden building with plenty of natural ventilation

Since the infiltration condensation problem was more or less solved, the topic now is diffusion condensation. As air-tightness increases by closing the gaps, the transfer of water vapor occurs not by airflow but by diffusion across the external wall according to the gradient vapor pressure (described in detail in 4.3.2). The conventional solution is to put a vapor barrier on the indoor side of the insulation layer and make the envelope vapor-tight. However this solution is only appropriate for the winter when the vapor transfer occurs from the interior to the exterior. This solution actually causes the risk of condensation in summer when the vapor transfer occurs from the exterior to the interior. This is a problem not only in Japan but also in other regions with a subtropical climate (see Figure 1-1). The most common risk evaluation method for diffusion condensation is the static calculation (see 2.2.1). Saito et al. have introduced a method using a dynamic simulation (Saito et al. 2006a, b). However, the general assumption of the model was based on the conventional solution with a vapor barrier, and so this method is not applicable to vapor-open systems, which would be a sound solution for the Japanese (or more generally, a subtropical) climate. There is no domestic commercial tool for transient heat and moisture transfer modeling which is capable of dealing with arbitrary boundary conditions on both sides of the envelope, even though theoretical studies have actually been done and a sophisticated model using the chemical potential of water as a driving potential was already introduced in the 1970's (Matsumoto 1978). It is not yet common to utilize such tools developed in other countries (introduced in detail in 2.2.1) in practical building design.

1.2.1.4 Energy efficiency of buildings

The first debate on the energy efficiency of buildings began after the oil shock in the same way as in the European countries. The Japanese government put the law regarding the rational use of energy into force in 1979. As with the European experience, the principle of the law was to enhance the economy while using less fossil fuel. After the adoption of the Kyoto Protocol in 1997, this law turned more in the direction of environmental concern. Regarding the housing industry, the revision made in 1999 defined the framework of the current energy standard (called "Next-generation Energy Standard") concerning the steady increase of energy consumption by households (Figure 1-7).

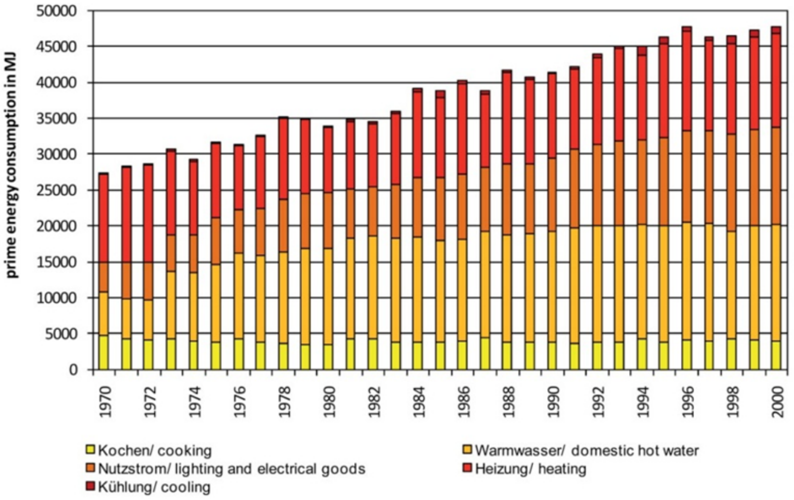


Figure 1-7: Increase of energy consumption by households in Japan

In Next-generation Energy Standard two evaluation guidelines for the energetic performance of housing are defined. One is a specific performance guideline in which heating and cooling demand and a heat transmission coefficient of a building as a whole (called "heat loss coefficient *Q*") is evaluated. The heat loss coefficient Q (W/m^{2}K), which is defined as heat transmission loss coefficient of the building, is the key indicator. Q-value is calculated by Equation (1.1),

$$Q = \frac{\left(\sum A_i \cdot U_i \cdot H_i + \sum \left(L_{FI} \cdot U_{Li} \cdot H_i + A_{Fi} \cdot U_{Fi}\right) + 0.35n \cdot B\right)}{S} \tag{1.1}$$

where A_i (m^2) is the area of building part i exposed to exterior air (wall, roof, window, etc.), U_i (W/m^{2}K) is the heat transfer coefficient of building part i, H_i (-) is the coefficient according to the type of the exterior air to which building part i is exposed (normal exterior air: 1.0, attic air which is connected to exterior air: 1.0, foundation void air which is connected to exterior air: 0.7), L_{Fi} (m) is perimeter length of the floor i directly connected to soil, U_{Li} (W/m^{2}K) is the heat transfer coefficient of the part which covers the perimeter of floor i directly connected to soil, A_{Fi} (m^2) is the area of floor i, U_{Fi} (W/m^{2}K) is the heat transfer coefficient of the center point of floor i, n (1/h) is the ventilation rate, B (m^3) is the volume of the building and S (m^2) is the gross floor area of the building. It should be noted that the Q-value is an original performance indicator in the guideline and different from the widely used heat transmission coefficient U (so-called U-value), even though the unit (W/m^{2}K) is expressed in the same way. This guideline defines the criteria of the annual heating and cooling demand and the Q-value according to the climatic division (see Figure 1-9).

The second is a specific design guideline in which the detailed requirement on the U-value of the envelope and openings is given.

Either of these guidelines is applied to evaluate the energetic performance of buildings. Table 1-1 lists the criterion of the heating and cooling demand and the Q-value in the specific performance guideline and the U-value in the specific design guideline (in the case of external walls of wooden buildings) according to the climatic division (see Figure 1-9). Those values are intended to ensure a 40% reduction of heating/cooling demand compared to the same building design without insulation. As of 2012 this standard is implemented as an “encouraged effort” only (no penalties for not complying) except for when a building with an area of 2 000 m^2 or more is newly erected/extended. Comparing this to the criterion of the Passivhaus standard (both heating and cooling demand must be below 15 kWh/m^{2}a, the European climate is comparable to that of Zone 1 and 2, see Figure 1-8 and 1-9), there is still great potential for improvement.

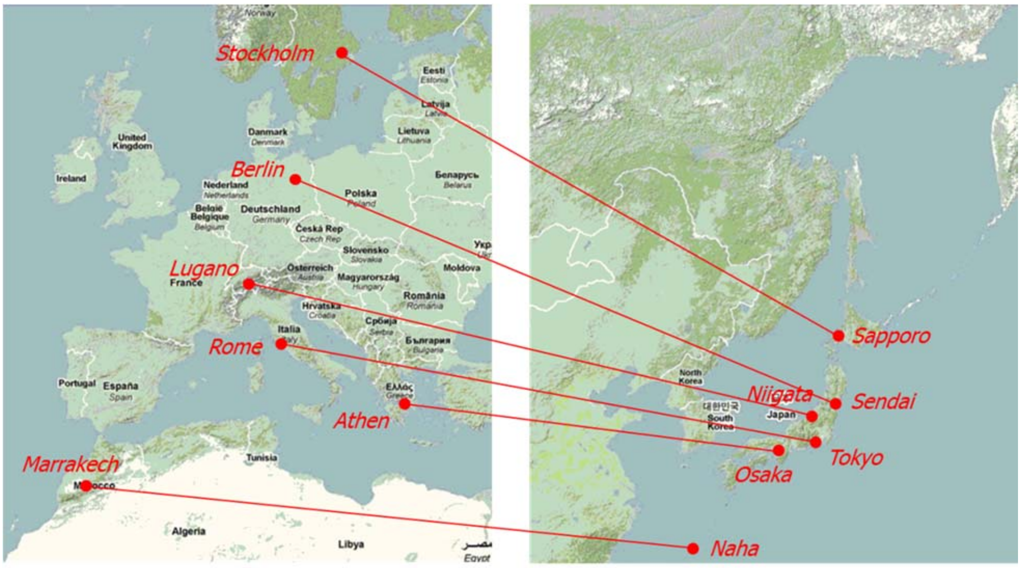
Table 1-1: Criterion of heating and cooling demand, Q-value and U-value according to the climatic division

	Zone					
	1	2	3	4	5	6
Heating and cooling demand (kWh/m^2a)	108	108	128	128	97	81
Q-Value (W/m^2K)	1.6	1.9	2.4	2.7	2.7	3.7
U-Value (W/m^2K)*	0.35	0.53	0.53	0.53	0.53	0.53

* The U-value of external wall of wooden building

1.2.2 Diverse Japanese climate

Japan has diverse climatic conditions due to its geographic characteristics. According to Köppen-Geiger climate classification, the northern regions have a continental climate (warm summer subtype) (Dfb), which is similar for example to the central Europe and southern Scandinavian regions. Under this climate, summer is mild, winter is very cold and the amount of precipitation is rather small. The central and southern regions have a humid subtropical climate (Cfa, see Figure 1-1). Under this climate, summer is hot and humid and winter is cold. It has a significant amount of precipitation in all seasons. Figure 1-8 shows the corresponding Japanese and European cities having the same heating/cooling degree days.



(map source: Google map)

Figure 1-8: The comparison of heating/cooling degree days between Japan and Europe

The Housing Industry Training Foundation (HITF) of Japan has conducted an extensive review of regional climatic diversity all over Japan, taking into account very detailed climatic factors such as temperature, humidity, wind direction and velocity, length of daylight, probability of clear weather and so on. Consequently it has been proposed that the built environment design should be based on the 14 divisions in which a total of 100 subdivisions are defined (HITF 1998).

The most widely accepted climate classification is the 6 zones division in accordance with the Japanese law on the rational use of energy in the housing sector (Act on the rational use of Energy, MLIT). Within this law the division of the zones has been based primarily on the heating and cooling energy consumption by buildings, which reflects the regional difference of local climate. This zoning is shown in Figure 1-9.

At any rate, this climatic diversity should be carefully taken into account as much as possible when discussing sustainable building designs.

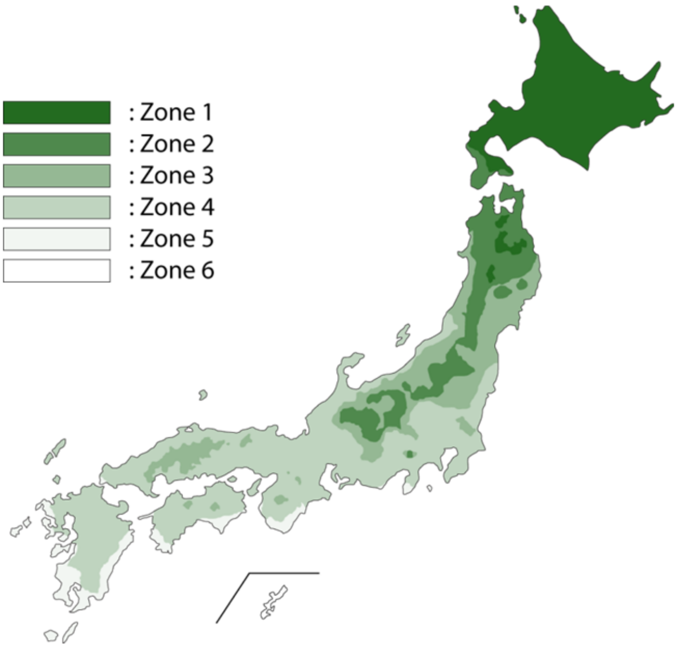


Figure 1-9: 6 Zones of Japanese climate according to Act on the rational use of Energy

1.2.3 Forest resource of Japan

Japan has another important issue in the wooden building industry regarding the use of domestic forest resources. Due to the heavy consumption of domestic wood, there was a major shortage of woods as raw material after the Second World. Therefore, large scale planting was conducted as a national policy after the war in order to secure the supply of wood. Today 66% of the land of Japan is covered by forest. 40% of the total forest is artificial forest and 50% is natural forest (the rest is bamboo forests and sparse forests). The artificial forest consists mostly of softwood. The main species are Japanese cedar (*Cryptmeria japonica*, *sugi* in Japanese), Japanese cypress (*Chamaecyparis obtuse*, *hinoki* in Japanese) and Japanese larch (*Larix kaempferi*, *karamatsu* in Japanese).

While the trees in the artificial forests grew, the importation of foreign timbers increased tremendously because of the rapidly growing economy of Japan after the war required timber as raw materials for all kinds of purposes. This resulted in a serious depression of the Japanese domestic forestry economy, mainly because the price of imported timbers became lower than the domestic timbers. Although Japan is very rich in forest resources, the degree of self-sufficiency on domestic wood (including paper/pulp and other industries) has largely decreased and fell below 20% around 2000 (Figure 1-10). It has been slowly improving in recent years because of a national campaign to promote the use of domestic wood, and it reached 26% in 2010. Figure 1-11 shows the share of the origin of imported timber and its usage in 2010. At the same time, the workforce is increasingly aging because of the very small numbers of new young entries into the work force. Therefore the area of abandoned planted forest is continuously increasing (Forest Agency 2011).

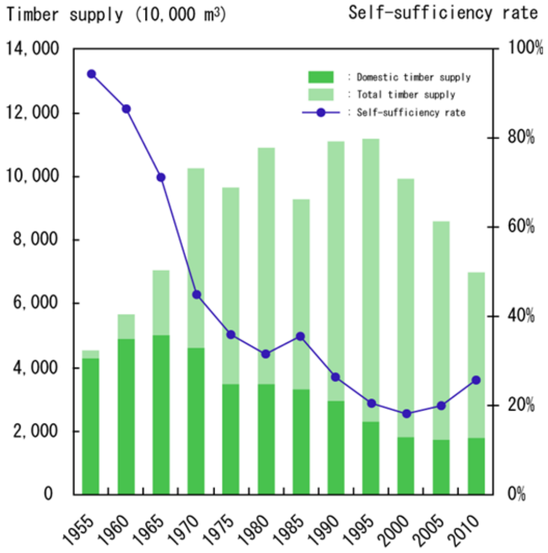


Figure 1-10: The degree of self-sufficiency of Japanese domestic timbers

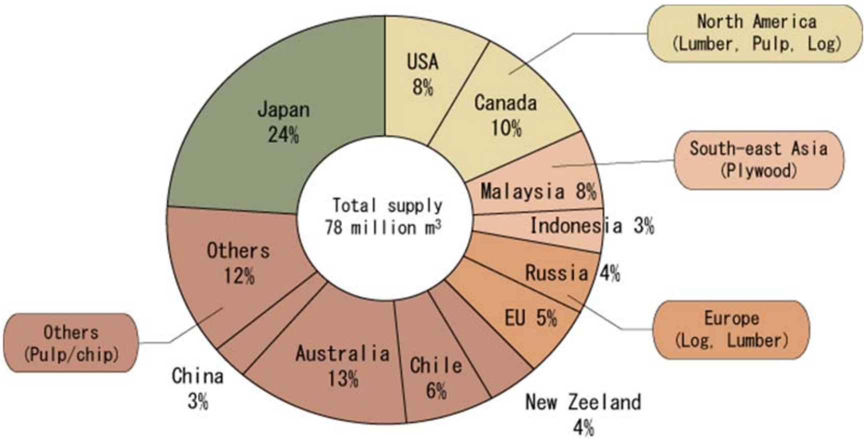


Figure 1-11: Share of the origins of imported wood products in 2010

This abandonment causes multiple problems. The planting is primarily done with a high density of seedlings. After about 15 years the first tree thinning is carried out, and afterwards the following thinning is done every 5 years until the felling of the fully matured trees (upper tree age of 45 years). Roughly 20% of the trees are cut for the thinning purpose. Timbers from forest thinning normally have small diameter and cannot be used as main structural elements of buildings, and so their value as material is not high, which means it creates limited economic profit. As the economy of the domestic forestry is already breaking down, forest thinning has not been sufficiently conducted. As a result the abandoned dense forests have been growing as they are. Then, new planting to secure the future timber supply is also not sufficiently carried out. Figure 1-12 shows the comparison of tree age composition of artificial softwood forest between 1985 and 2006.

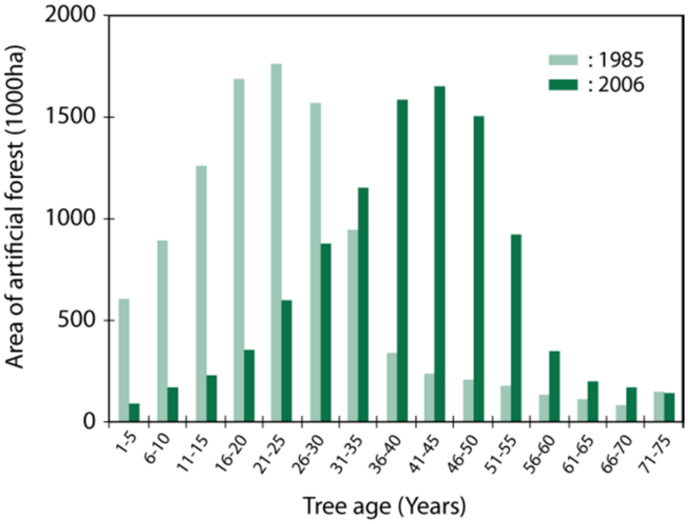


Figure 1-12: Comparison of tree age composition of artificial forest between 1985 and 2006

On a national scale and in the context of international affairs, the dense artificial forests have the problem of limited CO_2 absorption capacity. Within the Kyoto Protocol, CO_2 absorption by forest can be counted only when the forest is managed under human control. In that sense, the abandonment of artificial forests is a great concern regarding the international cooperation on global warming mitigation.

There are also considerable problems on the regional scale. The dense trees cause a lack of sunlight on the ground in these forests. Consequently, underbrush does not grow, which means the surface soil remains exposed to weathering. Firstly, this has an adverse effect on the biodiversity in the forest ecosystem. Secondly, the water retaining capacity of the soil greatly deteriorates. In the events of heavy precipitation, the rainwater is not absorbed into the soil but runs down the mountain slopes, which in the worst case results in flash flooding. Problems exist not only on the top of the soil but also in the soil. The high density of the trees means that the roots of trees are also too densely extended. Once the soil is stimulated by external force such as major earthquake or heavy rain, massive landslides occur more easily. The thinning of forests would have a significant influence on preventing landslides (Abe et al. 2004).

For conducting sustainable forest management, the Ministry of Agriculture, Forestry and Fisheries (MAFF) put the “Forest and Forestry Revitalization Plan” into force in 2010 (MAFF 2009). Its general short-term goal is to increase the degree of wood self-sufficiency to 50% by 2020. In the private sector, it is absolutely necessary to come up with measures that stimulate the forestry economy by creating profit and consequently increase the use of domestic timber. The key is to add values even to the unprofitable forest products such as thin timbers.

1.2.4 The latest situation of the Japanese housing industry

1.2.4.1 National policies

As reviewed above, the Japanese housing industry has issues on the rational use of energy and resources.

Regarding the use of energy, the awareness of consumers and constructors on the importance of energy efficient buildings has been growing more and more (MLIT 2007). The standard (publicized standards of judgment for residential construction clients) was enacted in 2009 in order to improve the average performance of new-built buildings. Within this standard constructors who produce more than 150 houses annually are advised to improve the energy efficiency of their products so that the average of the houses of one year is better than the former year (called the “leading runner approach”) over a certain period. This leading runner approach has been very successful in electric appliances and the automobile industry, and is expected to be successful in housing industry as well. As for actions to stimulate consumers, economic incentive approaches such as the reduction of interest rates on housing loans for high performing houses (Japan Housing Finance Agency) have been implemented and are achieving an effect (MLIT 2011b) utilizing a building evaluation tool such as CASBEE (Murakami et al. 2004) (see 1.1.3). After the accident of Fukushima Daiichi Nuclear Plant in 2011, the Ministry of Economy, Trade and Industry (METI) set forth a plan in which the current energy efficiency regulation becomes obligatory for all newly built buildings by 2020.

Regarding the use of resource, the primary issue is the increasing wood demand (Forest Agency 2011). The latest effort of the private companies, Building Research Institute and Forestry and Forest Product Research Institute, is to produce and utilize cross laminated timber (CLT) panels (Schickhofer et al. 2000) with the domestic resources. This is mainly aimed at the realization of multi-story wooden buildings accompanying the enactment of the new legislation to promote wood use in public buildings, such as office and school buildings (October, 2010). Under the current building code, CLT is not approved as a common structural element yet, and so the first effort is to prove its structural and fire safety performance (for example (Okabe et al. 2007) and (Sudo et al. 2007)) and to establish its industrial standard. Another challenge related to resource use is the longevity of houses. Traditionally the market of existing houses is very small in Japan compared to other countries (Figure 1-13) (MLIT 2011b). This is due to the tendency of Japanese consumers to prefer a brand-new house with a plan fit to the inhabitants' (the family's) demand. Because of the lack of structural flexibility of the conventional post and beam construction as well as the immature market of existing houses (information asymmetry and insufficient numbers of lawyers, specialized technicians and intermediate agents), existing houses, with plans that do not meet the demand of new inhabitants, tend to be demolished rather than renovated (Yamasaki 2005). This has resulted in a very short lifespan for houses in Japan (26 years (Ministry of Construction 1996)). Hence, a construction system with which the renovation of the plan is easily achieved and a greater market maturity are highly required.

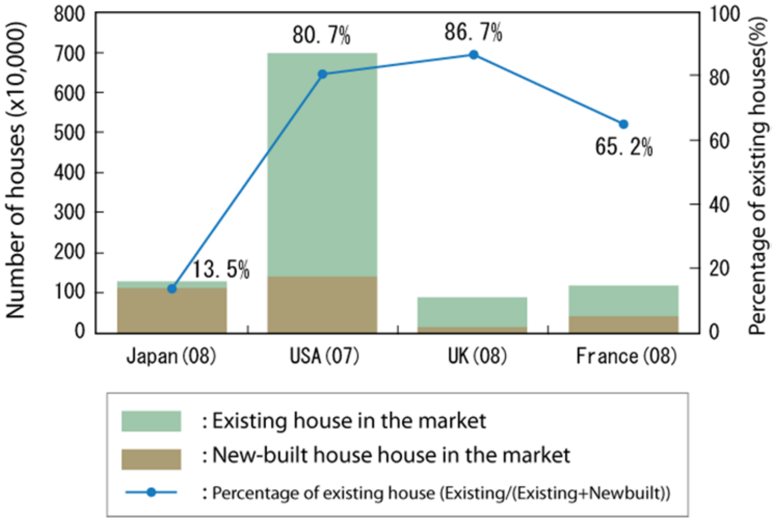


Figure 1-13: Comparison of the share of existing housing in the market

1.2.4.2 Up-to-date building technologies

The latest technical effort in the private sector related to energy consumption can be characterized by two measures, namely employing foreign technologies especially on energy efficiency and high-tech housing services, such as sophisticated heat pump, fuel cell and so on.

As for the foreign technologies, the implementation of the Passivhaus standard together with its evaluation method PHPP (Passivhaus Projektierungs-Paket) (Passive House Japan 2010) is a representative example. The first passive house was realized in Kamakura in 2009. This was a rather direct implementation of the original German Passivhaus Standard. Indeed the energy standard is more advanced in both the calculation method and the thermal performance criterion (Q-value is lower than 1.0 W/m^{2}K while the Next-generation Energy Standard (see 1.2.1.4) requires 2.7 W/m^{2}K in zone 4, where Kamakura is located (see Figure 1-9) (Passive House Japan 2010)). However, the climatic difference between Europe and Japan caused a problem when dealing with the humidity in summer, and the additional energy consumption for dehumidification of 25 kWh/m^{2}a was allowed in the certification criterion (Mori 2009). Considering that the criterion for the heating and cooling demand is 15 kWh/m^{2}a each, this is a significant compromise. The inhabitants are not supposed to open windows in order to ensure the performance, and this requirement goes considerably against their traditional preference of having plenty of natural ventilation as well. In general, when transferring knowledge and technology from one place to another and coming up with new solutions, the social acceptance as well as the local climatic conditions should be further considered. In the housing sector, there is much room for improvement in this regard.

As for building equipment, the installation of solar photovoltaic (PV) elements has been strongly promoted in the last decade as with other countries (IEA 2009), and the housing sector is no exception (New Energy Foundation 2008). The implementation of high-performing heat pump/HVAC units is also significant in recent years (Ministry of Environment 2008). In addition to these general situations, the characteristic effort in the housing industry is the development of the world’s first fuel cell for household use. The co-generation system using PEFC (proton exchange membrane fuel cell), called “ENE FARM”, was commercialized in 2009 and the reduction of primary energy consumption was investigated. The interesting finding is that the more hot water is consumed, the more primary energy consumption is saved (Bessho et al. 2010). This system is suitable in Japan considering the behavior of the Japanese (hot water consumption is very high due to frequent bathing). However, as the contribution of such equipment to the overall energy efficiency of buildings is assured when the envelope itself has proper thermal insulation performance, the interaction between building envelope and sophisticated building equipment should be carefully taken into account in the design of future buildings.

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2 Goal of the Study

2.1 Vapor-open wooden building envelope for Japan

In order to contribute to a more sustainable society and solve the problems mentioned in the previous chapter, a vapor-open wooden building envelope system was developed within the research project of “Nachhaltige Konzepte für Gebäudehüllen in Holzbauweise für Zentraljapan (Sustainable wooden building concept for central Japan)” funded by the Commission for Technology and Innovation CTI, (grant number: 9755.1 PFIW-IW) run by the Federal Department of Economic Affairs of Swiss Federation. The layered structure of the envelope system is illustrated in Figure 2-1 with a description of each layer’s component. The following 3 items characterize the design features of the envelope system:

- the use of environmentally friendly materials
- sorption-active and permeable construction
- flexibility in adjusting to local design conditions.

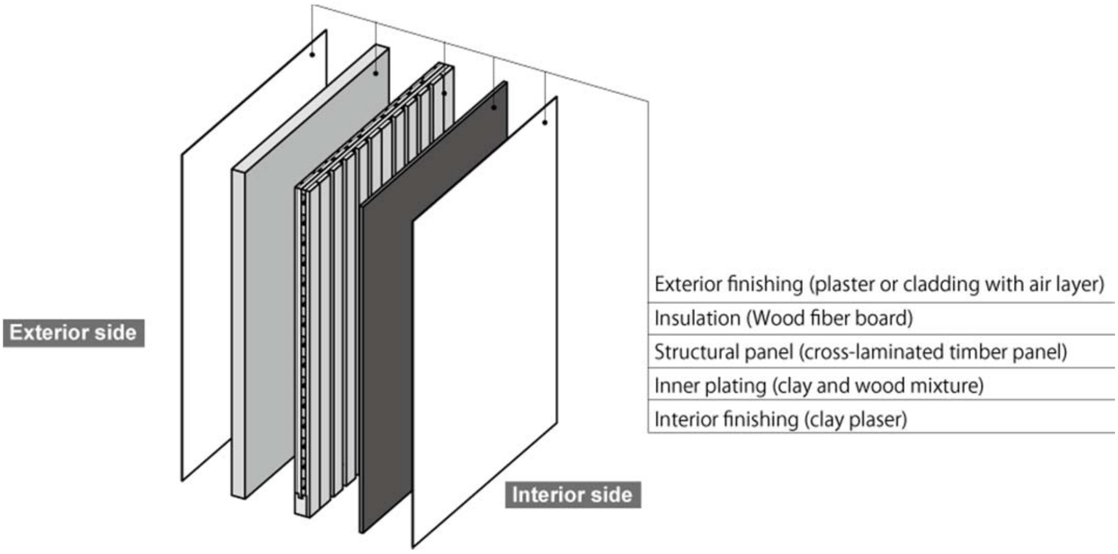

Figure 2-1: Layered structure of the envelope system

2.1.1 The use of environmentally friendly materials

The building materials are selected so as to minimize the environmental load. Two points are especially emphasized. The first point is that the material is not based on non-renewable resources. The second point is that the building components can be produced within local production lines with local resources. Therefore materials selected for the Japanese condition are wood, wood-based material and mineral based materials. The selected building components made with those materials are cross laminated timber, wood fiber insulation board, wood and clay composite board and mineral plaster.

2.1.2 Sorption-active and permeable construction

All building components are sorption-active and/or permeable in terms of water vapor because of its chemical composition and porous microstructure. The advantage of using such materials is that (1) the extreme moisture load or extreme dryness from the exterior/interior is buffered by the moisture adsorption/desorption property and (2) the excessive moisture load that is not adsorbed by the material is further transferred by diffusion to other points in or out of the envelope. The direction of moisture flux does not matter as long as it is assured that there will be no moisture accumulation. Hence, the issue of bidirectional moisture flux in subtropical regions is solved. When deciding the dimension of each component, it is important to consider that the adsorption/desorption and the vapor diffusivity are well balanced so that no moisture accumulation occurs inside the envelope.

2.1.3 Flexibility in adjusting to local design conditions

The energy efficiency of the whole building and the durability of the envelope are dominated by the internal/external heat and moisture loads. The external load is given by the local climatic conditions, such as the temperature and relative humidity of ambient air, precipitation, wind and sunshine. The internal load is caused by human activities, such as air conditioning, de/humidifying, use of electric appliances and so on. Those conditions differ from one place to another and from one group of inhabitants to another. Each envelope design must comply with both local design conditions and the expectation of durability.

The envelope has a layered structure: the interior finish layer with plastered wood-clay composite, the structural layer of cross laminated timber, the external insulation layer with wood fiber board and the façade with cladding or plastering. As explained in 2.1.2, the overall system allows the moisture flux to move through the wall in both directions, and it is possible to avoid moisture related problems inside the wall by defining the appropriate thickness for each layer. The unique point of this system is that each layer is independent and has its primary function. Each layer's component and dimension (thickness) can be changed according to the desired performance without interrupting the other layers. Therefore, for example, the thickness of the insulation layer, which gives not only the thermal resistance but also a moisture sorption capacity, can be independently determined according to the local climatic conditions. The material and dimension of the interior finish, which functions not only as thermal mass but also as a humidity buffer to stabilize the indoor climate, can also be determined according to the moisture load expected from the life style of inhabitants. Through this flexibility, an actual wall make-up can be determined very flexibly taking into account the specific design conditions of both sides of the envelope.

2.1.4 Other advantages of the envelope

Besides considerations regarding ecological impact and building physics, the design philosophy of the envelope also comprises economic and social aspects. Needless to say, the flexibility ensures the social acceptance of the technology. Furthermore, all the components have the potential to be produced locally as described in 2.1.1. Local production promotes the local economy creating a local value chain. The cross laminated timber panel has an especially high potential for addressing the timber resource problems of Japan. As shown in Figure 2-2, it consists of a large volume of wood slats with rather small sections. This means that the thin timbers from thinning forests could be used as the base material. From a legislative viewpoint, even though the Japanese building industry and governmental administration is rather conservative and so-called CLT is not approved as a common structural element, the cross laminated timber used in this system has a special approval to be produced with *sugi* (*Criptmeria Japonica*) timbers and to be used as a structural element. The application of CLT is highly expected to be one of the solutions for stimulating the wood-based material industry, which would result in the stimulation of the forestry economy and the improvement of the environmental function of artificial forests. The potential of CO_2 emissions savings by the domestic production of the panel is presented in Appendix D.

In addition to this, structures built with CLT elements offer another advantage for innovation in the Japanese housing industry. Unlike the conventional Japanese post and beam construction (see 1.2.1.2), the whole structure resists against external force like a rigid box because of the rigidity of the glued panel elements and the joints between the panels. Hence, the span of openings can be longer (6m at maximum). And the total length of the structural interior wall can be kept shorter. Consequently, it becomes possible to have a larger volume of space in buildings compared to the conventional construction systems, and to customize the floor plan with non-structural partition walls according to the taste of inhabitants. It ensures the longevity of the construction by avoiding the obsolescence of the house as a product (see 1.2.4.1).

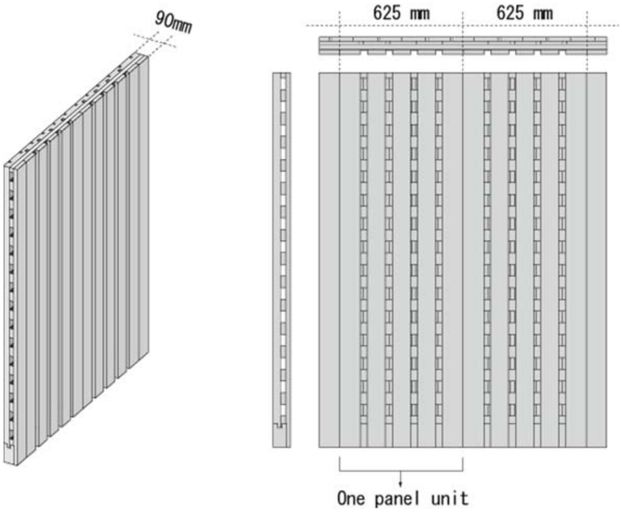

Figure 2-2: Composition of the cross laminated timber panel

2.2 Validation methodologies

The performance of the envelope needs to be validated by scientific measures. In this thesis, the items to be dealt with using scientific quantification were selected as follows: the hygrothermal performance of the envelope, the energetic performance of a building with the envelope system and the economic and ecological optimal insulation thickness of the envelope. While the specific purpose of these studies was to evaluate the feasibility of the envelope system under Japanese conditions, it should be noted that the chosen/created modeling described below are general methods and are applicable to other construction systems and regions as well.

2.2.1 Hygrothermal performance of the envelope

In order to investigate durability, the hygrothermal performance of the envelope was analyzed by numerical and empirical methods: transient heat and moisture transfer modeling and experiments with full-scale wall specimens.

The analysis of heat transfer in external walls has been of great interest since the insulating of buildings has been recognized as the most important measure to make buildings energy efficient. There are widely known basic theories of heat transfer by conduction (Fourier’s law), convection Newton’s law of cooling) and radiation (Planck’s law), and nowadays tools to simulate three dimensional steady state and dynamic heat transfer are in practical use in the industry (for example TRISCO and VOLTRA (PHYSIBEL)).

Yet, heat transfer is not the only phenomena to be considered. As mentioned in 1.2.4, the moisture transfer in exterior walls plays a significant role in the durability of buildings. In order to assess the moisture accumulation in walls and roofs, steady state models such as the Glaser-method ((Glaser 1959) and (SIA 180 1999)) and the Kieper-method (Kieper et al. 1976) are widely used. With the aid of those methods, the risk of interstitial condensation is analyzed with simple equations and charted under a given solid boundary condition. Furthermore, because of the remarkable development of computing technology in the last decades, one or two dimensional dynamic simulation models of coupled heat and moisture transfer have been developed, validated and become commercially available (for example WUFI (Künzel 1995), MOIST (Burch 1997), 1D-HAM (Hagentoft et al. 2000), DELPHIN (Grunewald 2000) and so on). With these dynamic simulation tools, more realistic simulations applying the actual climatic data has become available using each components material properties (thermal conductivity, vapor permeability, specific heat capacity, porosity, moisture storage function (equilibrium moisture content), liquid water transport property and so on). These tools are highly reliable when modeling the moisture transfer under the conditions associated with indoor conditions (10-40°C, 0-100%RH and no contact with liquid water). However, there remains a need to improve methods for modeling exterior weathering, especially the modeling of the interaction between façade and wind-driven rain. The insufficient consideration of the occurrence of splashing/bouncing of rain drops and the surface moisture evaporation/absorption results in significant simulation error (Abuku et al. 2009). The models must be carefully created considering the actual building design and this shortcoming of modeling.

In this thesis, WUFI was selected as the tool to model the heat and moisture transfer across the envelope because of the sound theoretical background, high reliability and the user-friendliness (which is actually a very important point for wide acceptance in the industry). Experiments with full-scale wall specimens were conducted with climate simulation chambers, and the temperature and relative humidity inside the wall specimens were measured. The exterior and interior climatic conditions were extracted from the experiments and were applied to the simulations by WUFI as the boundary conditions. Then the predicted and measured temperature and relative humidity inside the walls were compared to each other, and the simulation model was validated as to whether it is a usable tool for assessing the moisture accumulation risk or not. Furthermore, the model was applied to real climatic condition of a Japanese city (Kyoto) to investigate whether the climate would cause moisture accumulation in the wall.

2.2.2 Energetic performance of a building with the envelope

In order to investigate the energetic performance of a building with the envelope system, a model was created to simulate the indoor temperature, relative humidity and the heating and cooling demand, combining the hygrothermal model of the envelope itself, heat balance model of the whole building and the moisture balance model, taking into account the interaction of the envelope and ambient air.

The whole building simulation created to model the energetic performance has been of great interest recently, mainly because of the necessity of predicting heating and cooling demand of buildings. The factors that may have an influence on the indoor climate are largely categorized into two groups. One group is the external factors. Those are exterior air temperature, exterior humidity, solar radiation, wind, precipitation, neighboring environment (shading by neighboring trees and buildings), soil temperature, terrestrial radiation, moisture evaporation from soil and so on. The other group is the internal factors. Those are active heating/cooling of indoor air, de/humidification, ventilation with/without heat/moisture exchange, opening/closing of windows, opening/closing of shading, heating load from electric appliances/lights, heating load from human activities (human body, cooking), moisture load from plants, moisture load form human activities (human body, cooking, bathing and laundry), heat buffering by thermal mass, moisture buffering by interior materials and so on. Those factors are illustrated in Figure 2-3

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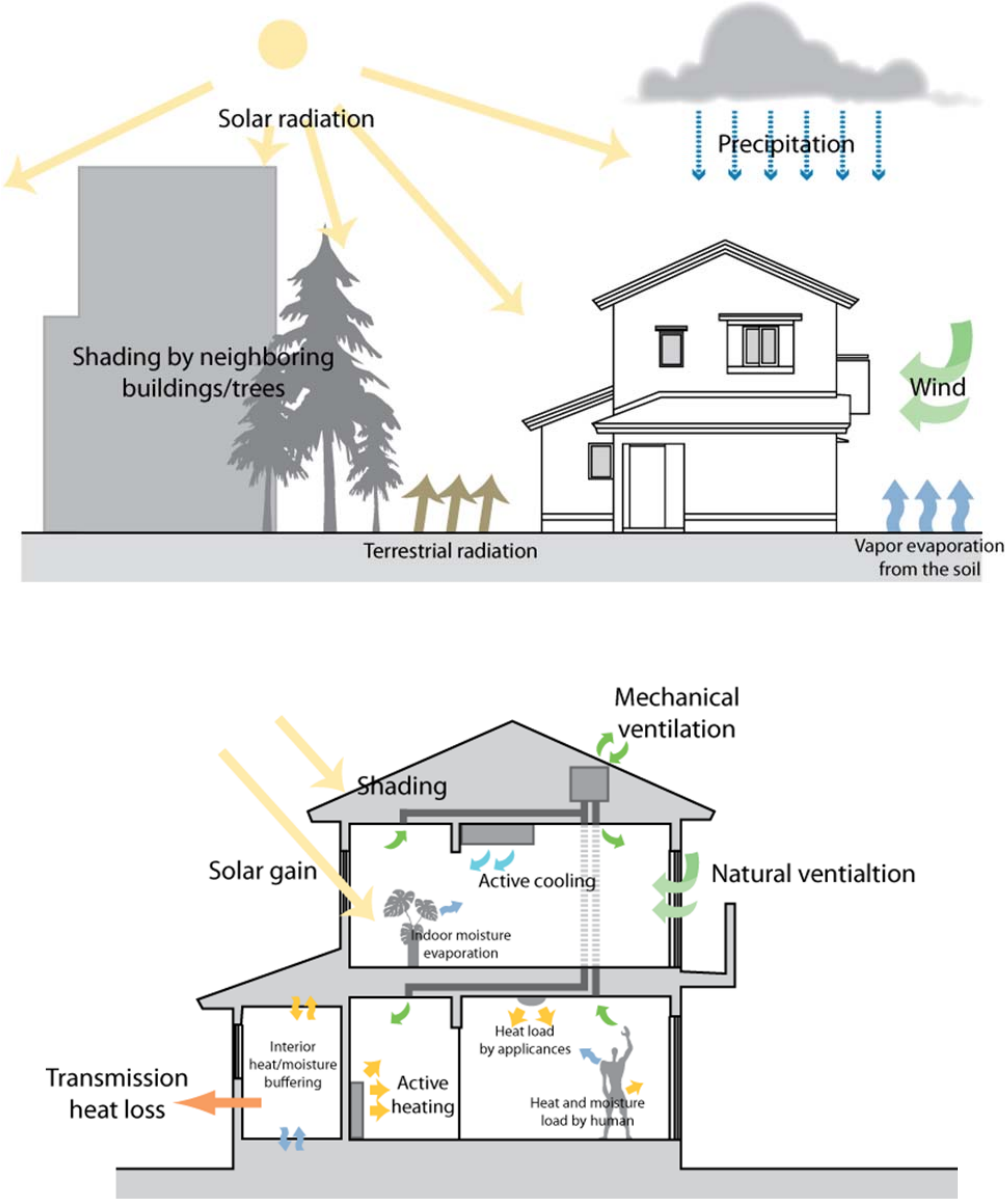

Figure 2-3: External and internal heat and moisture load factors

The interactions among these factors and across the building envelope and openings (doors and windows) need to be calculated by balancing them with each other. As long as only the heat balance is concerned, the ISO has already established the standard “Energy performance of buildings – Calculation of energy use for space heating and cooling” (ISO 13790 2007). Also the moisture balance simulation has attracted more and more attention since moisture content of indoor air (humidity) has a significant influence on the comfort and durability of the envelope. A number of whole building simulation tools have been developed, and some of those are commercially available (for example BSim (Rode et al. 2003 and 2004), EnergyPlus (Henninger et al. 2004), TRNSYS (Klein et al. 2004), WUFI-Plus (Holm et al. 2003)). Each tool has its own detailed setting and none of them use the same method for dealing with the moisture transfer. For example, the moisture interaction between ambient air and the envelope are modeled in BSim and WUFI-Plus, but this is not the case with EnergyPlus and TRNSYS. The material properties dependent on the moisture content are thoroughly considered in WUFI-Plus and partly in BSim (only vapor permeability), but not at all in the others. In terms of the granularity of the modeled volume(s), WUFI-plus only deals with a single zone model while the others are capable of multi-zone modeling. A detailed comparison of whole building heat and moisture balance simulation tools can be found in (Woloszyn et al. 2008).

Considering the usage of the envelope system in subtropical regions, moisture buffering by interior material is worth being taken into account. In fact, there have been a number of studies on the integration of moisture buffering in the building design process regarding the achievement of a more stable room climate and energy efficiency (for example (Padfield et al. 2004) and (Rode et al. 2008)). Osanyintola et al. pointed out that energy consumption is significantly reduced in a subtropical climate by enhancing the moisture buffering of a room’s interior (Osanyintola et al. 2006). The whole building simulation tools introduced above have different ways of modeling the moisture interaction between the interior and room air by buffering, and all of those are simplified model based on the equilibrium moisture content, which does not deal with, for example, the dynamic change of moisture sorption capacities of the interior materials and the non-linear effect of micro scale moisture ad/desorption into account.

As briefly reviewed here, each tool has its advantages and shortcomings. In this thesis, rather than employing the commercial tools, a new structure of whole building heat and moisture balance simulation was created in order to include a model of the indoor moisture buffering function, not by the simple conventional method but by a more sophisticated one, including the dynamic change of moisture sorption capacities. The general purpose of the simulation is to predict indoor air temperature, humidity and heating/cooling load. The simulation consists of four steps. Step 1 is the transient heat and moisture transfer simulation across the wall with WUFI. In this step, the optimum layer construction, which does not have permanent moisture accumulation in the wall, is identified by applying the method described in 2.2.1. In Step 2, the dynamic heat balance simulation is carried out by Helios (Frank et al. 2006) in accordance with ISO 13790. The input for this simulation is the wall make-up identified in Step 1 and parameters such as the set-point temperature and ventilation rate as well as the outdoor climate. The time-dependent room temperature and heating/cooling load is calculated and used in Step 3, which is the simulation of moisture balance. In this dynamic moisture balance simulation, the time-dependent relative humidity of a room is predicted by introducing a moisture flow due to air exchange between the exterior and interior, internal moisture load and the moisture buffering by the interior materials. The moisture buffering is the predicted value based on a model validated by empirical data. Finally in Step 4, the predicted indoor temperature and humidity is used as the boundary condition of the transient simulation across the wall, which is done once with the tentative boundary indoor condition in Step 1. Once it is confirmed that there is no interstitial condensation with the predicted room condition, the optimization of the wall make-up and therefore the heat and moisture balance simulation is completed. The whole structure of the simulation is illustrated in Figure 2-4. By defining a design set-up of a model building and its location, a case study of indoor climate and heating/cooling load prediction was carried out. The general plans of the building used for this case study is presented in Appendix A.

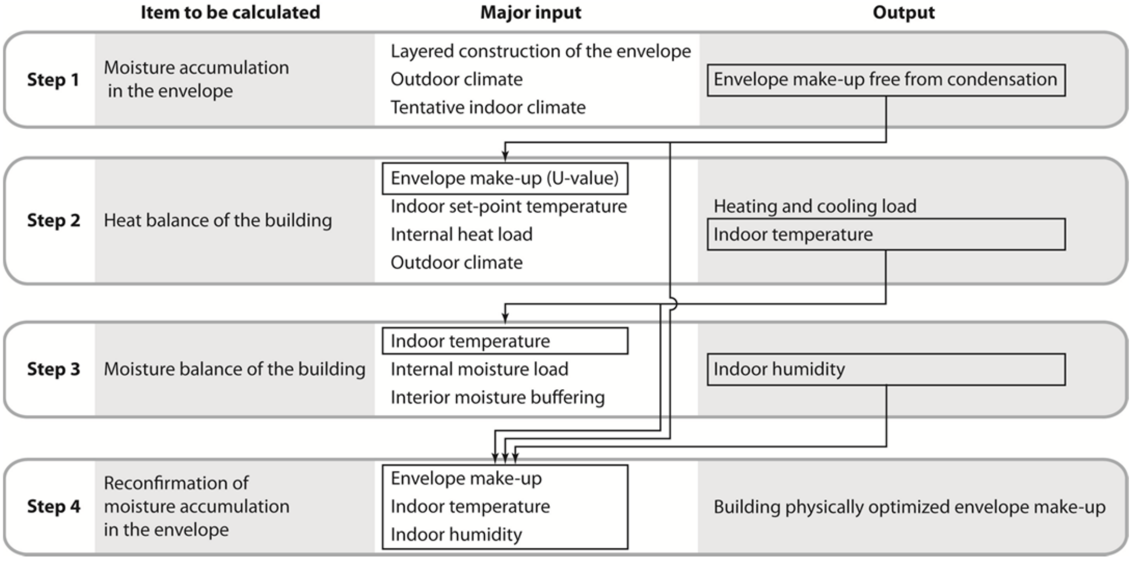

Figure 2-4: Structure of the whole building heat and moisture simulation

2.2.3 Economic and ecological optimal insulation thickness

In order to investigate the feasibility of applying the envelope system under Japanese conditions, the model to define the economic and ecological optimal insulation thickness of the model building was created using the transmission heat loss model described in 2.2.2, a simplified Life Cycle Assessment (LCA) and the Life Cycle Cost Assessment (LCCA) method. In the optimization model several scenarios were considered to take into account the uncertainty of the future economic situation.

LCA is a commonly accepted method to evaluate environmental impacts due to the production and use of goods and services. Since the early 1990s, a number of preliminary studies have been carried out with an emphasis on waste reduction and on a broader concern for later balancing resource and energy use (Hunt et al. 1996). The methodology is nowadays based on the ISO standard “Environmental Management Life Cycle Assessment Principles and Framework” (ISO 14040 2006). In ISO 14040 LCA is defined as: “A technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts; and interpreting the results of the inventory analysis and impact assessment phases.” The indicator used to quantify the environmental load depends on the interest. A large number of internationally accepted environmental indicators exist (Althaus et al. 2010), such as Cumulative Energy Demand (CED) (VDI 1997), the CO_{2eq} factors from the Intergovernmental Panel on Climate Change (IPCC 2007 100a and IPCC 2007 500a) (Albritton et al. 2001), IMPACT 2002+ (Jolliet et al. 2003), Ecological footprint (Huijbregts et al. 2007) and so on. Those indicators should be carefully used since each method has a different focus to be analyzed and different modeling assumptions.

LCCA has an evaluation focus on the economic aspect of products. The purpose of LCCA is to calculate the lifetime cost of production and use of goods and services. LCCA is often used as an estimation tool in the design phase of products in order to minimize their lifetime cost. Therefore the design features that largely affect the lifetime cost are the primary concerns in the assessment. The balance of initial and running costs is the key to minimizing the lifetime cost. Regarding the cost of a building, the initial cost consists of purchase costs (the cost of buying building components, land and so on) and construction costs (the cost of construction work, transportation of components and so on). The running cost consists of fuel costs (the cost to run appliances and to regulate the indoor climate) and operation costs (the cost for maintenance, repair and replacement of the building or a part of the building). In addition to that, the cost for demolishing the building also needs to be taken into account.

In order to minimize the lifetime cost of buildings, the reduction of fuel costs, especially the cost for heating, is the most important point due to its large share of the lifetime cost (Marceau et al. 2006). The minimization of lifetime cost by defining the optimal insulation thickness has been studied using a variety of conditions and costing methods. Hasan investigated the optimal insulation thickness and payback period against the initial investment for the insulation under the condition of Palestine (Hasan 1999). Boermans et al. conducted an analysis with the conditions of Europe and provided the recommended insulation thickness (Boermans et al. 2008). The transmission heat loss model of those studies was based on heating degree days, in which climatic conditions other than the external temperature cannot be taken into account. Jaber et al. conducted an optimization analysis of the insulation of a residential building under the Mediterranean climatic conditions of Jordan using a sophisticated transmission heat loss model by TRNSYS (see 2.2.2) (Jaber et al. 2011).

In this thesis, a simplified LCA and LCCA method was applied to a building model with the envelope system, and the assessment result was compared to each other in order to investigate the economic and ecological optimal insulation thickness. Figure 2-5 shows the general concept of how the optimal insulation thickness resulting in the lowest lifetime cost was defined. The best practice is achieved by the optimal insulation thickness, but it is not a very strict point to be aimed for. Reasonable good solutions actually exist both to the left and right of the optimal point. In the present study, an optimal 10% range (the range which is defined by less than 110% of the optimal cost) was considered. The optimal thickness range was then defined by the overlapping of each optimal 10% range.

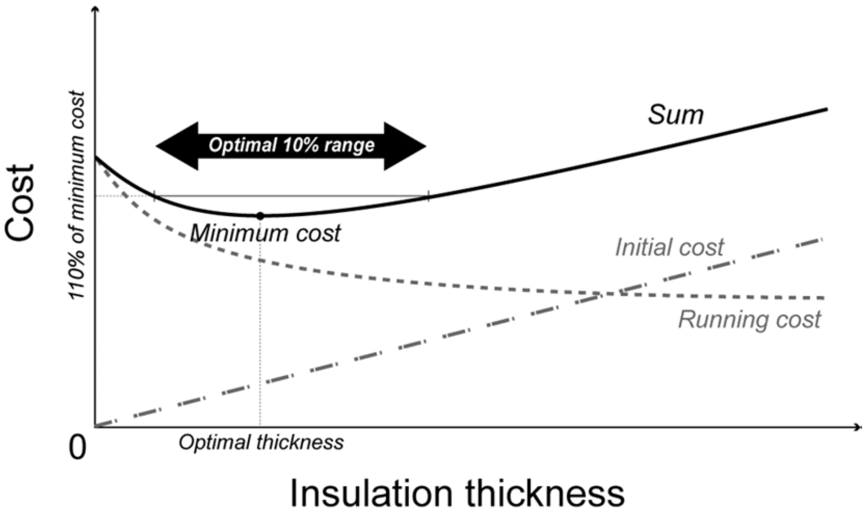

Figure 2-5: The definition of optimal insulation thickness

Regarding LCA, ecological impact was interpreted as “ecological cost”. Five methods (CED, IPCC 2007 100a, IPCC 2007 500a, IMPACT 2002+ and Ecological footprint) were used in order to have a broader interpretation of ecological impact. The Japanese local condition of primary energy mix was applied. The weighting within each method was carried out using the LCA software SimaPro (PRé Consultants bv). Regarding LCCA, only the initial cost for purchasing the insulation material and energy cost for heating/cooling was taken into account based on the assumption that there is no need for insulation maintenance as long as there are no mistakes in the construction work. As general settings within both the LCA and LCCA, the transmission heat loss calculated by the heat and moisture balance model proposed in 2.2.2 was used so that the heating/cooling demand can reflect the local climatic conditions and inhabitants’ behaviors. The transportation of material and the cost of the construction work were disregarded. As for the definition of the service life of the insulation, it was dealt with separately from that of the building itself. Therefore the demolition of the insulation (namely the repair/replacement of the insulation) has less cost/impact than that of the entire building and was disregarded in the assessments.

The optimal insulation thickness range derived from these assessments was examined as to whether it is thicker than the minimum insulation thickness to avoid moisture-related problems. This minimum insulation thickness was defined by the heat and moisture balance model proposed in 2.2.2 using the local climatic conditions of cities in Japan.

As mentioned in 1.2.4.1, there is a substantial degree of uncertainty regarding the future of the Japanese economy and environmental issues. Hence, a sensitivity study with the parameters of the interest rate of Japanese currency, energy price increase rate and the mix of primary energy was carried out and the applicability of the envelope was discussed.

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3 Preliminary Investigation of a Vapor-open Envelope Tailored for Subtropical Climate (Paper I)

Abstract

Concerning global warming and resource depletion, the impact of buildings in subtropical regions is becoming even greater due to a high growth rate of urbanized areas. From the viewpoint of building physics, the main problem concerning subtropical climate is the high level of humidity in combination with high temperature. In this study, a flexible building envelope consisting of wood and clay components was developed so that the materials and the assemblies can be easily tailored to comply with local climatic conditions. The movement and accumulation of moisture in the wall was of prime concern. This has been investigated by means of testing full scale walls in a climate chamber and the corresponding one dimensional transient heat and transfer simulation. In order to achieve a consistency between calculation and measurement, the individual materials were tested for their hygric and thermal properties. Based on these findings attempts were made to calculate the behavior of an optimized wall assembly under real climatic conditions of central Japan. As a result, it was shown that the hygrothermal behavior of the envelope is predictable by means of the models and the simulation program used, and that no risk of interstitial condensation and mold growth was predicted under the real climatic conditions of Kyoto.

Goto Y., Ghazi Wakili K., Ostermeyer Y., Frank T., Ando N., Wallbaum H.: “Preliminary investigation of a vapor-open envelope tailored for subtropical climate”. *Building and Environment* 46(3): 719-728, 2011.

3.1 Introduction

3.1.1 General background

In regards to reducing CO_2 emissions worldwide, the building sector is recognized to be of great importance. For example, within European Union, the emissions caused by the production of building materials, construction processes and operation consumptions of buildings amount to up to 30% of the total CO_2 emissions (CIB 1999). Considering the impact of building sectors, developing areas must also be taken into account due to a high growth rate of urbanized areas (CIB&UNEP-IETC 2002). While dealing with this issue, it is important not only to take measures for reducing CO_2 emissions, but also to consider holistic approaches, such as the triple bottom line model of sustainability that demands ecological, economic and social performances:

- Ecological sustainability: the environmental load over the complete life cycle should be as low as possible. This includes that of the production of the building materials, construction processes and the operation consumptions until the demolition/disassembly phase.
- Economic sustainability: the initial investment in higher quality or better ecological performance should pay off eventually.
- Social sustainability: providing inhabitants with a comfortable and healthy living environment. The house should be able to adapt to changes in life style.

The exact measures to be taken to reach this goal while maintaining comfort and avoiding damage caused by moisture are generally not agreed upon. The general discussion is whether to focus on passive measures such as the envelope, active measures such as heating/cooling systems and energy generation, or a change in user behavior. A central point however is that certain minimum effort has to be made in all areas in order to achieve the goals listed above. This is especially true for the building envelope since a sound concept for this part of the building will greatly affect its lifespan.

An additional issue arises when building technologies are transferred and adapted to climates and cultures other than from where they originated. As the demand in many countries for knowledge on energy reduction in the building sector is rising, the need for a sound approach that adapts to regional conditions is likewise present (Murakami et al. 2004). The question of transferring building know-how and technologies in the field of building envelopes from a northern European climate to other parts of the world has already been discussed. Zirkelbach et al. (Zirkelbach et al. 2004) have investigated the application of external thermal insulation composite systems applied to the climates of, among others, Tokyo, Dubai and Bangkok. In addition to the energy-related advantages, their simulations with the respective weather data demonstrated the problem of moisture accumulation in the outer walls in hot and humid climates.

This study describes the performance and concept of a building envelope that was created for such problematic climate conditions, in this case central Japan.

Based on the demands for sustainability, the following targets were set in the project:

- Long lifetime: The building should not succumb to damages due to lack of adaptation to the local cultural and climatic conditions therefore:
    - The wall has to be kept free of condensation and mold/fungi.
    - The systems should enable flexible adaptations to the changing demands of inhabitants.
- Low environmental load: The envelope should have a low environmental impact in the production, handling and recycling phase.
- No harmful substances: The building materials must not contain or emit any toxic compounds that affect the living environment.

These targets comply with the triple bottom line model explained above.

A preliminary investigation of the hygrothermal behavior of such a building envelope tailored especially for different climatic zones of Japan is presented here. Japan has a very wide range of climatic diversity and its subtropical climate is similar to those of the east coast of China, the northern part of India, the southeast coast of South America and so on. Furthermore, there is still a strong need for energy efficiency/savings in the Japanese residential sector. Recently, attentions have been paid to both passive and active measures for better performance of the buildings in terms of energy consumption (Murakami et al. 2007). But the issue of energy efficiency was associated more to the building equipments than the building envelopes (for example Lopes et al. 2005). Meanwhile, Japan has a long tradition of poorly insulated wooden buildings for residential use. The life style of the Japanese people especially on heating and cooling is still being influenced by its tradition. Accordingly, when Japanese building sector started implementing the European building technology such as super insulated and air-tight houses to Japanese buildings, undesirable building physical problems such as overheats in summer have been observed (Sdei 2007). Therefore there is a strong need for a sustainable building envelope system which complies with local climate and user behavior.

This study has been done in four steps:

- measuring the main hygrothermal properties of the used materials in detail

  in a climate chamber
- building up two different walls and testing their response to temperature and moisture load in a climate chamber

- simulating the hygrothermal behavior of the mentioned walls using the measured properties and test conditions as input, and comparing calculated and measured results
- applying real Japanese climate data to the numerical calculation.

3.1.2 Design concept of the building envelope

3.1.2.1 Vapor-open construction for subtropical climate

From the viewpoint of building physics, the primary complexity of the Japanese climate is its extreme difference of temperature and humidity between summer and winter. Regarding the Mediterranean or continental climates, the point to be carefully considered is the moisture flux during winter, flowing from interior side to exterior side. Most often the solution is to block the humidity from entering the wall from the inside. The same winter conditions must be taken into account in central Japan. However, summers in Japan are different from the European Mediterranean climate, combining high temperatures and high relative humidity. As a result of cooling and dehumidification to acquire room comfort, the moisture flux will flow from the exterior to the interior side, a fact that must be considered in designing the wall assembly.

Based on these boundary conditions, it appears unfeasible to protect walls against the moisture flux by applying any type of vapor barrier that is designed for one-way moisture transfer. A suitable envelope for such climatic conditions must enable moisture transfer in both directions and simultaneously avoid moisture accumulation and interstitial condensation. An additional aspect that has to be taken into account is the frequent occurrence of earthquakes, which is prone to damage any kind of barrier over time and hence results in the ingress of humidity. A solution to this problem is an envelope that is open to moisture transfer and has adequate vapor diffusion resistance and vapor buffering function.

3.1.2.2 Selection of materials

By approaching this problem with the use of a vapor-open concept, the hygric properties of the materials must be given in depth consideration in addition to their thermal properties. Table 3-1 shows the list of materials and their function in the assembly. On the interior side, two different panels of wood and clay mixtures were used as moisture buffering materials with increased thermal capacity. As thermal insulation material, wood fiber boards with slightly different properties were chosen. A cross-laminated wooden panel was chosen as a structural element. It consists of a continuous wood sheet, two layers of parallel wood slats, one turned 90 degrees with respect to the other and finally two layers of parallel wood slats, one staggered against the other (Figure 3-1). Taking the environmental load due to production into account, all materials can potentially be produced domestically using local materials.

Table 3-1: Materials selected based on the sustainable concept

Material	Kind of material	Function
Wood/clay mixture 1	High density wood and clay mixture	Inner plating
Wood/clay mixture 2	Low density wood and clay mixture	Short term moisture buffer against interior air
Wood fiber board 1	Low density wood fiber board	External thermal insulation Long term moisture buffer against exterior air
Wood fiber board 2		
Wood fiber board 3		
Wood fiber board 4		
Cross-laminated wooden panel	Glued softwood slats	Structural panel

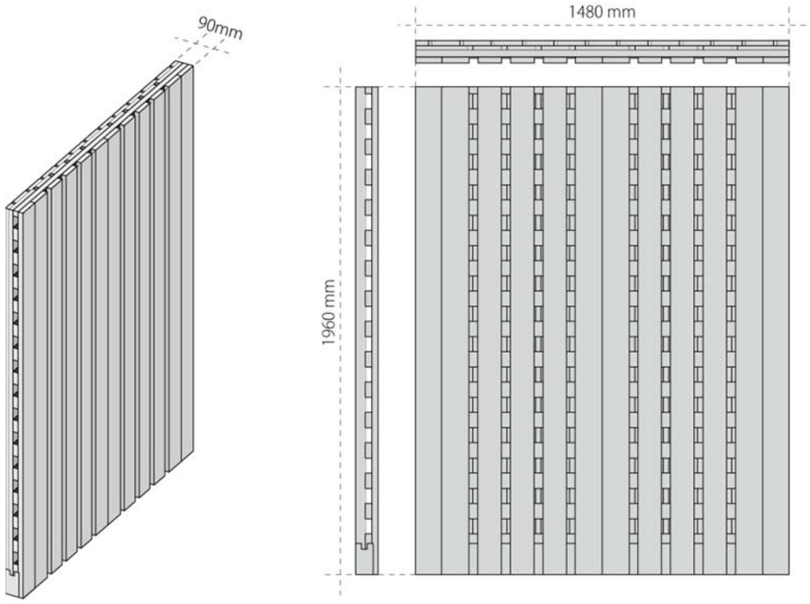
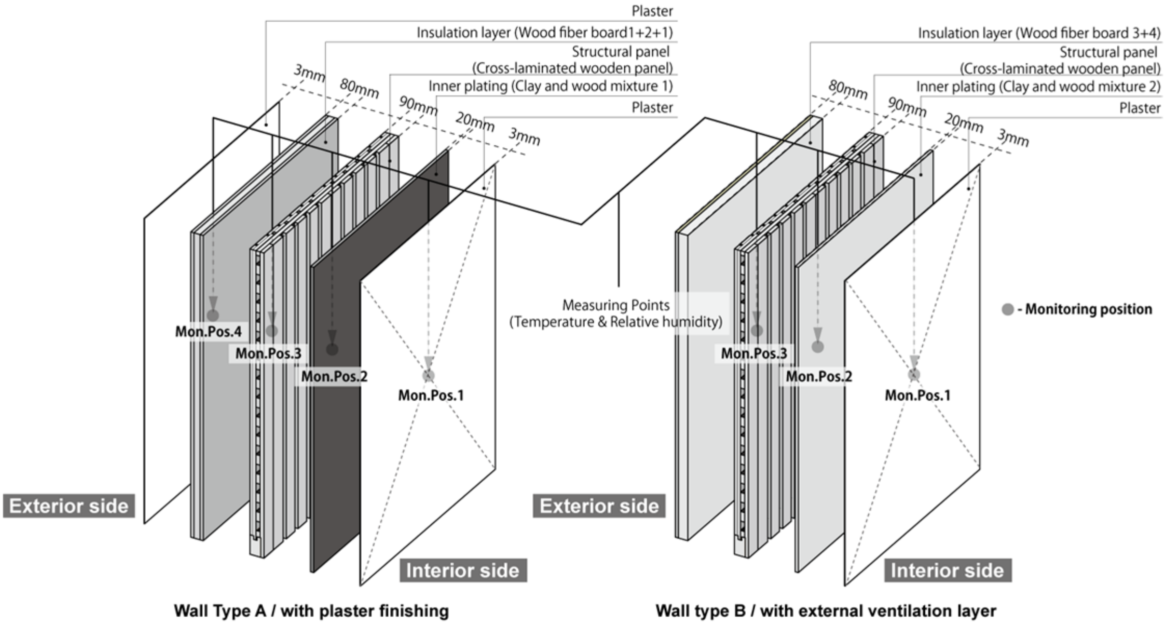


Figure 3-1: Geometry of cross-laminated wooden panel

3.1.2.3 Construction of the envelope

Figure 3-2 shows two wall assemblies investigated in this study. Wall type A is a simple externally insulated wall with an exterior finishing of a 3 mm plaster layer and a panel of wood and clay mixture on the interior side with a plaster finishing. Wall type B is also an externally insulated wall, but with a claddings on its exterior surface which includes an air gap open to natural ventilation. Because the cladding itself is not relevant to hygrothermal behavior of the assembly, this element was neglected in the wall specimen and the calculation. Wall type B is also an externally insulated wall, but with a ventilation layer on the weather side. For this reason, no plaster was applied to the exterior side of the insulation layer. On the interior side, a panel of wood and clay mixture was applied, again with plaster finishing. In addition, a wind-tight membrane which has little impact on heat and moisture transport was also put between the insulating layer and the structural element of both wall types. The advantage of having a layered construction system is that no posts or any other building components interrupt the individual homogeneous layers. This enables the material of each layer and its thickness to be selected independently, for its primary function alone. Hence, allowing a degree of flexibility where a detailed assembly of wall constructions can be decided upon according to the design condition of local climate and inhabitants' behavior.



Wall Type A / with plaster finishing

Wall type B / with external ventilation layer

Figure 3-2: Test specimens as examples of the wall make up

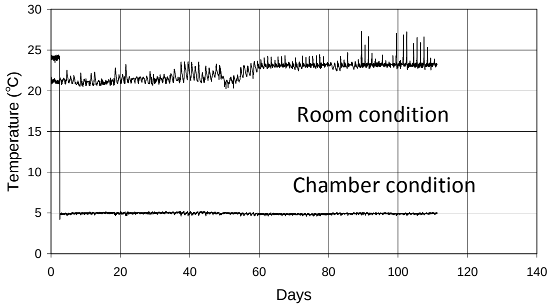
3.2 Climate chamber test

For investigating the hygric and thermal performance of the wall assemblies, a full scale wall specimen of each wall type was constructed (1480 mm x 1960 mm), and subjected to defined boundary conditions on both sides. Temperature and relative humidity across the walls were measured at different sites. The measuring points and material thicknesses are given in Figure 3-2. The walls were fixed air and moisture tight to climatic simulation chambers. These have openings of 1500 mm x 2000 mm and can be regulated to simulate the exterior temperature and relative humidity conditions (hereafter called chamber condition). The other side of the wall is exposed to the laboratory condition (hereafter called room condition). The climate chamber and the test piece of wall type A are shown in Figure 3-3.

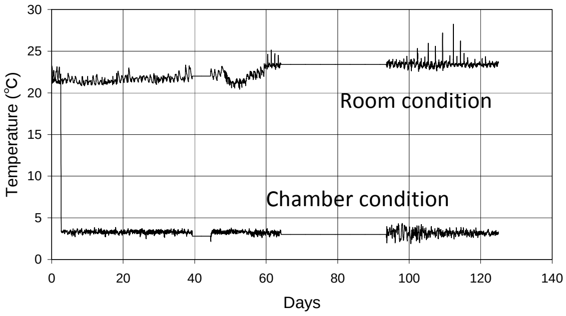
Figure 3-3: Climate chamber (left) and test piece (Wall type A) (right)

In this experiment, the chamber condition was assumed to represent the exterior climatic condition, and the room condition whose temperature was controlled around 23°C was assumed to represent the interior climatic condition. In order to see the possibility of interstitial condensation occurring, the chamber condition was set to create a critical situation, namely the combination of low temperature and high level of relative humidity. In the case of wall type A, the temperature of the chamber condition was set around 5°C (Figure 3-4a), and its relative humidity was set to rise gradually from an initial state of 20% to a steady state of around 90% (Figure 3-5a). In the case of wall type B, the temperature setting (Figure 3-4b) was similar to wall type A, and its relative humidity was set to rise gradually from about 20% to around 60% (Figure 3-5b), as in reality the external ventilation will reduce the moisture load. In addition to these basic conditions, large and abrupt humidity steps were generated in room conditions in the middle of testing periods of both experiments. This was for investigating the buffering performance against such a sudden moisture load assuming a realistic living environment.

The data measured by calibrated humidity and temperature sensors were collected every half hour during the testing period. The measured data collected from the wall specimens were saved on a data logger. . Some sensors failed to collect data in certain periods due to unexpected electrical interruption. In detail, as for the wall type A, the sensors for both the temperature and the relative humidity at monitoring position 1, 2, 3 and 4 failed from the day 38 to 50. As for the wall type B, the sensor for both the temperature and relative humidity of chamber and room condition failed from the day 38 to 45 and from the day 65 to 92. The sensors for the temperature at the monitoring position 1, 2 and 3 failed from the day 38 to 45. The sensors for measuring the relative humidity at the monitoring position 1, 2 and 3 failed from the day 38 to 50 (see Fig. 3-4, 3-5, 3-7, 3-8, 3-9, 3-10). Since the calibration of all sensors after the measurement showed no significant difference from that of the beginning, these gaps were closed by assuming linear connections between adjacent points.

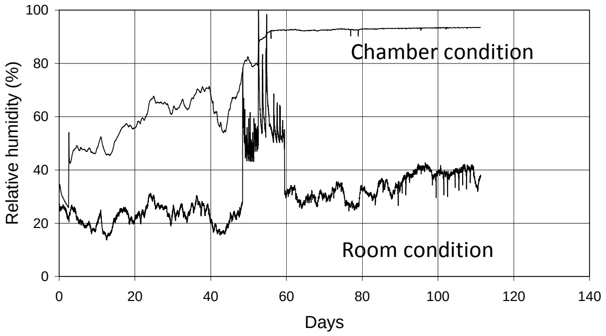


(a) Wall type A

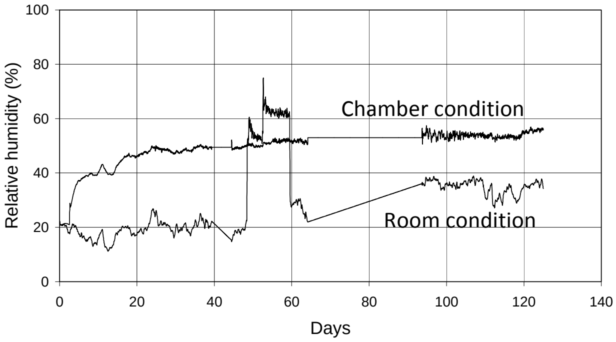


(b) Wall type B

Figure 3-4: Measured temperature used as boundary conditions for Wall type A (a) and B (b)



(a) Wall type A



(b) Wall type B

Figure 3-5: Measured relative humidity used as boundary conditions for Wall type A (a) and B (b)

3.3 Transient hygrothermal analysis

3.3.1 One dimensional transient heat and moisture simulation

When developing a new construction method, it is also important to establish a design method which can be applied to various designing conditions flexibly. Considering the versatility of designing method, it is a reasonable option to make use of the established ones. For the climatic conditions of Japan, Saito et al. (Saito et al. 2006a and 2006b) have established a simple design method which gives the requirement for the moisture resistance ratio of wooden wall assemblies to avoid problems caused by condensation. Although this method was validated by means of experiments and numerical simulations, it can be applied only to Japanese conventional post and beam construction with the limitation of climatic conditions. For calculating the heat and moisture transfer across the wall developed in this study, it is suitable to use the programs which can model the multilayer building components and can take the moisture sorption property and moisture dependence of the hygrothermal properties of each elements. Numbers of such simulation tool have been developed (for example (Bygge- og Miljøteknik AS) and (Hagentoft et al. 2000)) up to now.

WUFI Pro 4.2® is one of those PC programs with which transient one-dimensional heat and moisture transport in multi-layered building components can be simulated taking driving rain and solar radiation into account (Künzel 1995) (Fraunhofer-Institute for Building Physics). In this program, the moisture transfer is based on vapor diffusion and liquid transport, and then two coupled equations for heat and moisture transfer are solved simultaneously. Several studies have been done for validating WUFI® program. Kalamees et al. (Kalamees et al. 2003) made validation study comparing several similar simulation programs. Evrard (Evrard 2008a) carried out the study on utilizing composite materials made of lime binder and hemp particle for the use of heat and moisture regulation. Both studies concluded that WUFI® can be used for the prediction of the hygrothermal properties of layered assemblies. On the other hand, it must be noted that several physical phenomenon cannot be modeled. The most relevant one is the retarded sorption effect (Evrard 2008b). Besides this point, there is an uncertainty when calculating the moisture transfer under the condition with continuous existence of liquid water. Since the focus of the experiment described above was not to measure every single fluctuation but the overall behavior of the humidity without direct contact to liquid water, in this study, this program has been considered as adequate.

In the initial phase of the project the relevance of spatial conditions such as outer edges and their impact on the results of the modeling were discussed. It was concluded that, as the critical conditions are always to be found in summer, the respective points, which are known to be critical ones in European winter conditions, actually perform better that the regular make-up. In order to make the results easier to understand and limit the complexity a one dimensional modeling approach was chosen.

The material properties required in this calculation method regarding heat and moisture transfer are as follows:

- thickness
- moisture-dependent thermal conductivity
- moisture storage function (sorption isotherm)
- moisture-dependent water vapor diffusion resistance factor
- bulk density in dry condition
- specific heat capacity
- liquid transport coefficient for suction and redistribution
- Overall porosity.

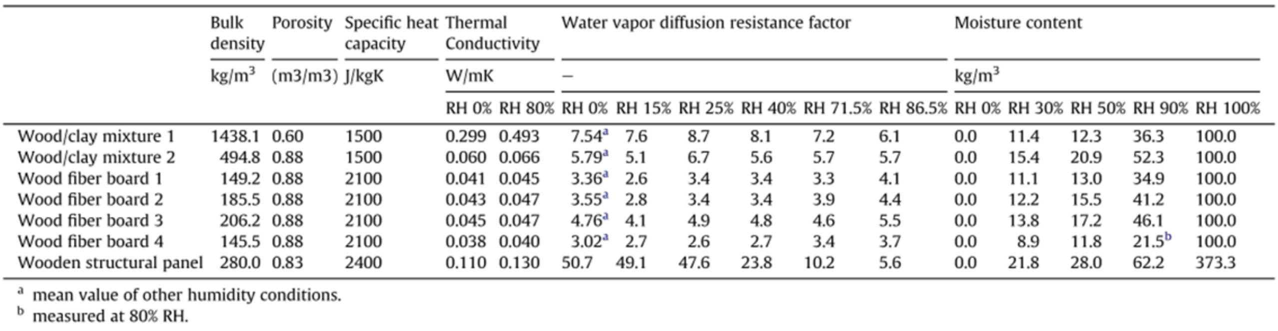
3.3.2 Determination of material properties

Conventional or assumed values tend to be used for describing hygrothermal characteristics of building materials when using numerical simulations. In reality, several material properties are depending on their moisture content so that a single value is not accurate enough. Such moisture dependent properties differ from one material to another and also from one producer to the other, as many of them must fulfill different requirements (Clarke et al. 2009). For acquiring more credible numerical simulations, the material properties of the building components that are moisture-dependent were measured as functions of moisture. These were the thermal conductivity λ (W/mK), the moisture storage function and the water vapor diffusion resistance factor (hereafter called μ-value).

The thermal conductivity was measured by the guarded hot-plate method (ISO 8302 1991). Before the measurement, samples of each material were conditioned at 23°C / 80%RH and 105°C / 0%RH until they reached equilibrium (constant mass) and cooled down to ambient temperature. By these two extreme values, a linear moisture dependence of the thermal conductivity could be determined. The moisture storage function was measured by the climatic chamber method described in (ISO 12571 2000) at 23°C and with at least four different values of relative humidity (0, 30, 50, and 80 or 90%RH). For the super saturated region (95-100%RH), the value of 100 kg/m^3 was assumed as a first approximation for all wood and clay mixtures and wood fiber boards. The μ-value was measured by the cup method (ISO 12572 2001) under different humidity gradient and humidity mean values (0% - 30%, 0% - 50%, 0% - 80%, 93% - 50% and 93% - 80%). For the calculation models, the mean values of wood and clay mixtures and wood fiber boards were used as the results showed no significant moisture dependence.

This was not the case for the structural panel made of solid wood slats. First of all, the thermal conductivity was calculated by means of a 3D thermal model taking into account the different air layers. This resulted in an effective value for the thermal conductivity. The moisture dependence of this parameter was assumed by an increase of 1.0% per mass percent of moisture uptake. The effective density was determined by making a weighted average of air (1.0 kg/m^3) and wood (450 kg/m^3). The μ-value was measured for representative part of the structural panel and used to determine the effective μ-value accordingly. For the specific heat capacity, the value of solid wood was chosen, as the contribution of the air layer is negligible. In the hygrothermal model, these effective properties define the homogeneous layer representing the complex structure panel. For the moisture storage function, the effective values were calculated by reducing the values for solid wood by the corresponding density factor i.e. ρ_{panel} / ρ_{wood}= 0.62. This was regarded as an admissible approximation since the interest of the study was not in the moisture distribution within this structural panel but in its boundaries to the adjacent homogeneous layers. Table 3-2 summarizes all physical properties of the materials required for the calculations. Those extracted from the literature (Künzel HM 1995) (Fraunhofer-Institute for Building Physics) (ISO 10456 2008) are shaded in gray. Wood and wooden products show a measurable hysteresis behavior in their moisture uptake and release (Derome et al. 2008a). This effect is however small and hence neglected in the present preliminary study.

Table 3-2: Measured and assumed material properties



	Bulk density	Porosity	Specific heat capacity	Thermal Conductivity		Water vapor diffusion resistance factor						Moisture content				
	kg/m^3	(m3/m3)	J/kgK	W/mK		–						kg/m^3				
				RH 0%	RH 80%	RH 0%	RH 15%	RH 25%	RH 40%	RH 71.5%	RH 86.5%	RH 0%	RH 30%	RH 50%	RH 90%	RH 100%
Wood/clay mixture 1	1438.1	0.60	1500	0.299	0.493	7.54[a]	7.6	8.7	8.1	7.2	6.1	0.0	11.4	12.3	36.3	100.0
Wood/clay mixture 2	494.8	0.88	1500	0.060	0.066	5.79[a]	5.1	6.7	5.6	5.7	5.7	0.0	15.4	20.9	52.3	100.0
Wood fiber board 1	149.2	0.88	2100	0.041	0.045	3.36[a]	2.6	3.4	3.4	3.3	4.1	0.0	11.1	13.0	34.9	100.0
Wood fiber board 2	185.5	0.88	2100	0.043	0.047	3.55[a]	2.8	3.4	3.4	3.9	4.4	0.0	12.2	15.5	41.2	100.0
Wood fiber board 3	206.2	0.88	2100	0.045	0.047	4.76[a]	4.1	4.9	4.8	4.6	5.5	0.0	13.8	17.2	46.1	100.0
Wood fiber board 4	145.5	0.88	2100	0.038	0.040	3.02[a]	2.7	2.6	2.7	3.4	3.7	0.0	8.9	11.8	21.5[b]	100.0
Wooden structural panel	280.0	0.83	2400	0.110	0.130	50.7	49.1	47.6	23.8	10.2	5.6	0.0	21.8	28.0	62.2	373.3

[a] mean value of other humidity conditions.
[b] measured at 80% RH.

3.3.3 Simulation model

The geometries and the mesh divisions of the models are shown in Figure 3-6. The monitoring positions are indicated by circles and correspond to the actual measuring points in the experiments. The surface heat resistance used in the models was determined numerically by getting the best fit for the measured and calculate surface temperature. This is because applying conventional values, which are designed according to real climatic condition, for such simulations is not appropriate considering the conditions of the experiments, which were conducted indoors. The plaster finishing on both sides of the walls were taken into account only by S_d-values (the equivalent air layer thickness in terms of water vapor diffusion), as their thermal impacts are negligible. For the boundary temperature and relative humidity on both sides, the measured values during the experiments were used. The time step for calculations was set at 30 minutes. The defined calculation periods corresponded to the duration of the experiments. The surface transfer coefficients used in all calculations are stated in Table.3-3.

Table 3-3: Surface transfer coefficients for the numerical simulations

		Exterior Surface		Interior Surface	
		Heat Resistance m^2K/W	Sd Value m	Heat Resistance m^2K/W	Sd Value m
Wall type A	Validation study	0.03	0.075	0.08	0.043
	Kyoto climate	0.0588	0.075	0.125	0.043
Wall type B	Validation study	0.015	0	0.015	0.057
	Kyoto climate	0.0588	0	0.125	0.057

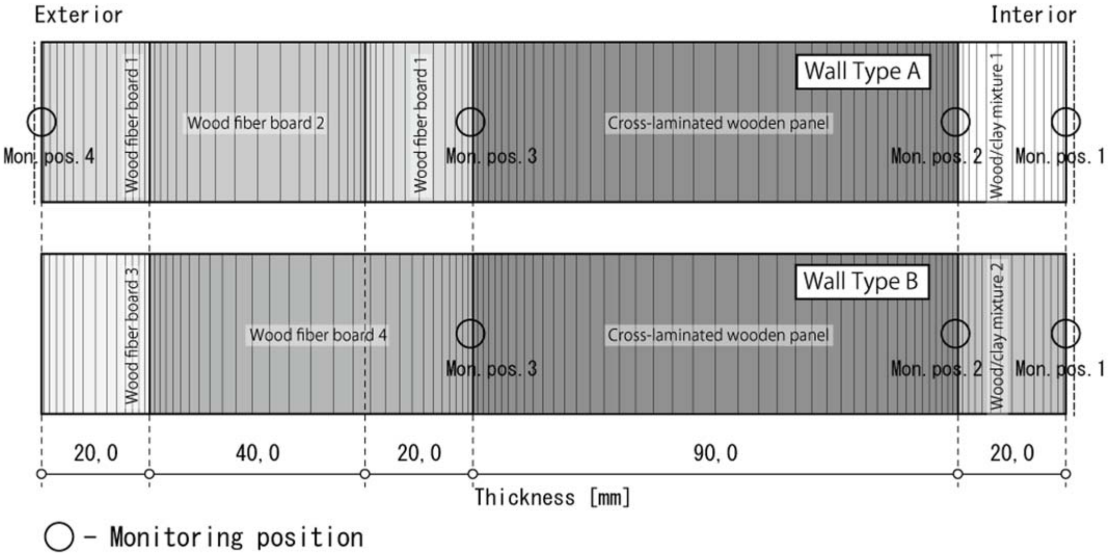
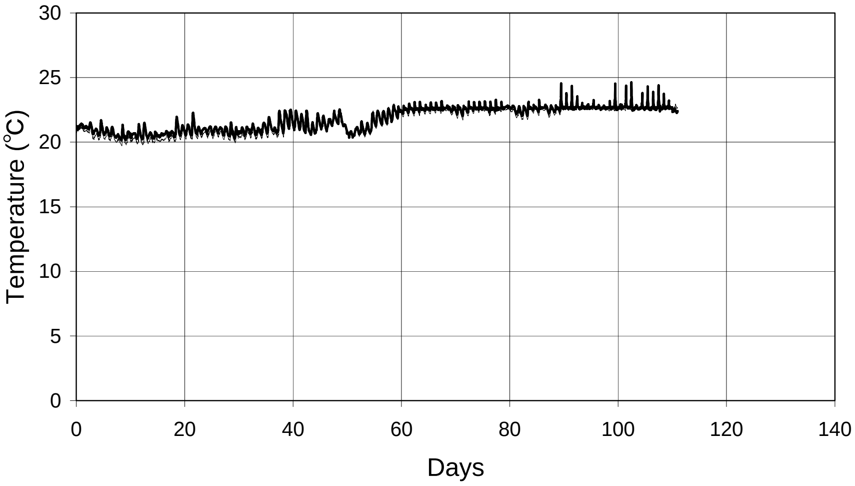


Figure 3-6: Geometry and mesh division of the simulation models

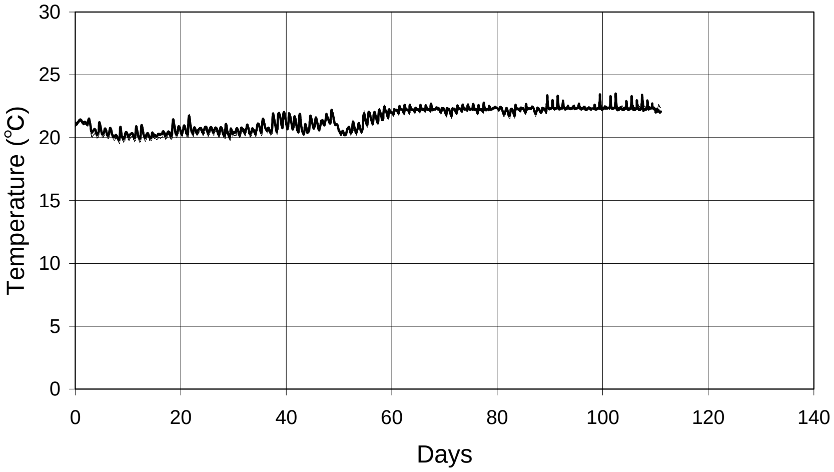
3.4 Result & Discussion

3.4.1 Comparison of measured and calculated results

Measured and calculated temperature and relative humidity at different sites of the two walls A and B are presented in Figure (3-7)-(3-10). These show an approximately constant surface temperature difference over both Wall types A (Figure 3-7a-d) and B (Figure 3-9a-d) of 18°C during the period of 110 days. There is a jump in the relative humidity from 20 – 65%RH for a period of 15 days on the room side of both wall types (Figure 3-8 and 3-10). Regarding Wall type A, both measured and calculated temperature and relative humidity correspond satisfactorily. As for Wall type B, the calculated temperatures fit the measurements well. The relative humidity at different sites follows the shape of the measured values but is shifted by an amount of 5%. Small changes in the material properties did not affect this gap hence this might be due to the calibration of the humidity sensors. Impact of air leakage between the wall and climate chamber can be ruled out because the humidity would be more likely to enter the chamber (5°C) than escape from it.

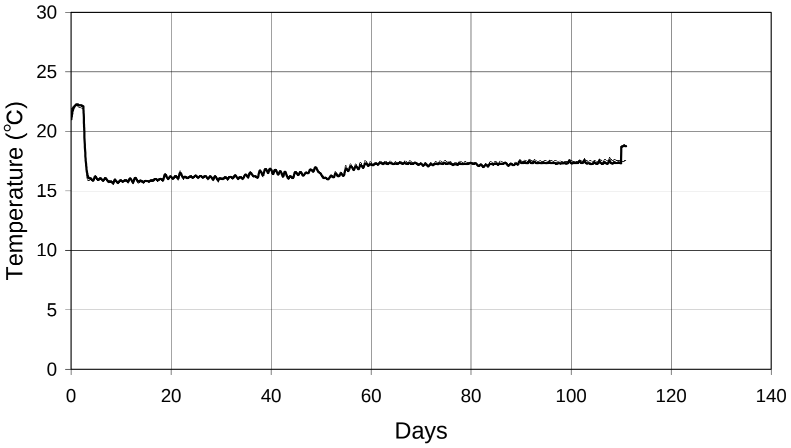


(a) Mon. Pos. 1

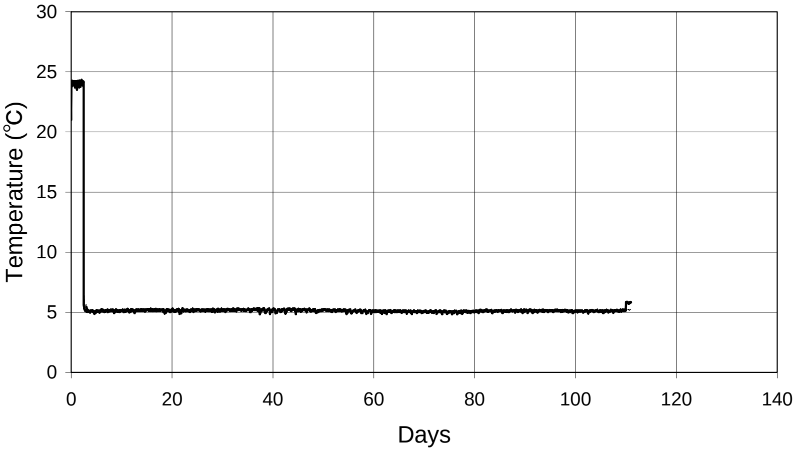


(b) Mon. Pos. 2

Figure 3-7: Temperature at different positions of Wall type A: calculation (thick lines) vs. experiment (thin lines)

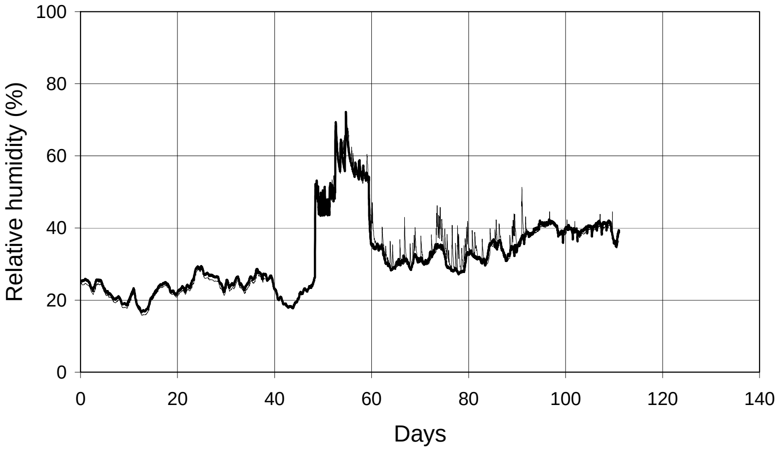


(c) Mon. Pos. 3

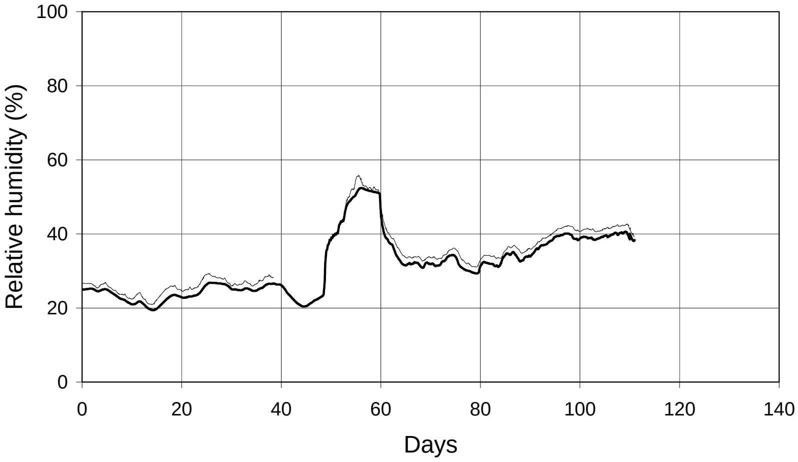


(d) Mon. Pos. 4

Figure 3-7 (cont.): Temperature at different positions of Wall type A: calculation (thick lines) vs. experiment (thin lines)

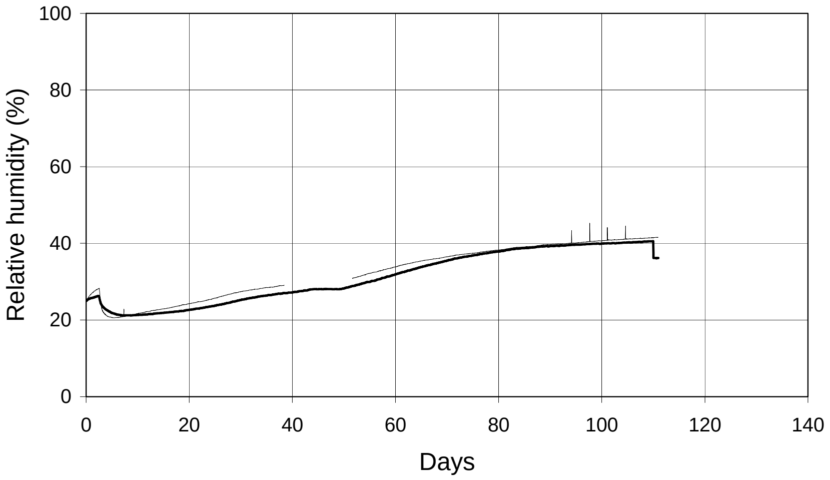


(a) Mon. Pos. 1

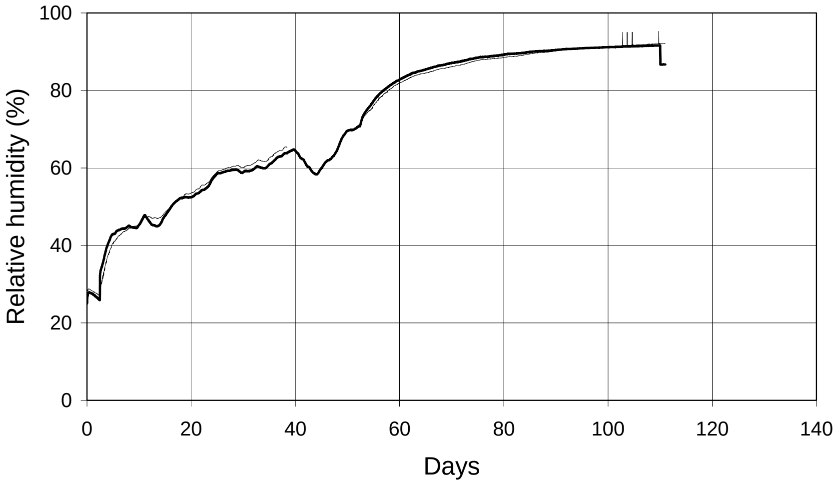


(b) Mon. Pos. 2

Figure 3-8: Relative humidity at different positions of Wall type A: calculation (thick lines) vs. experiment (thin lines)

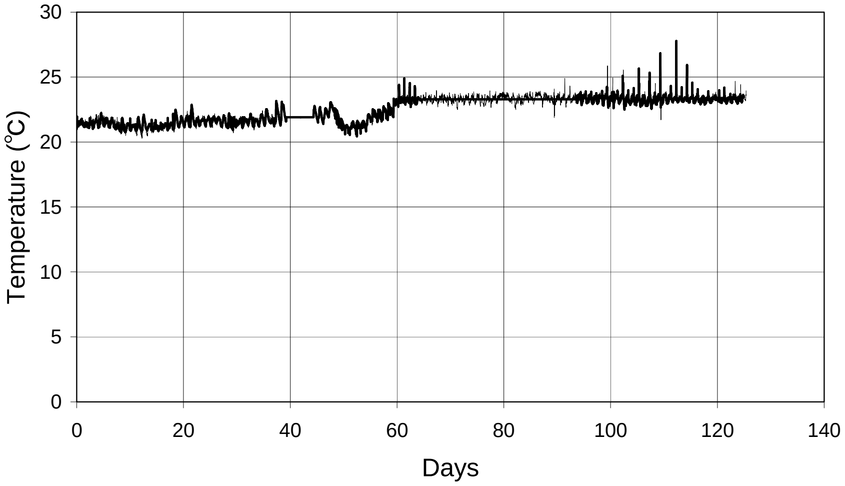


(c) Mon. Pos. 3

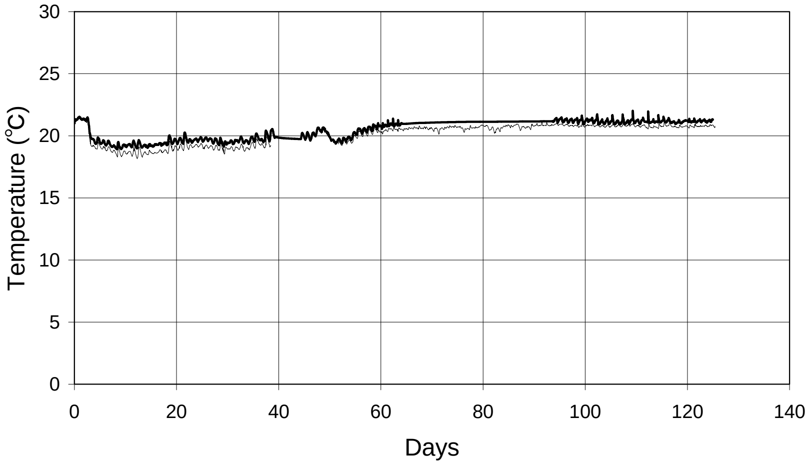


(d) Mon. Pos. 4

Figure 3-8 (cont.): Relative humidity at different positions of Wall type A : calculation (thick lines) vs. experiment (thin lines)

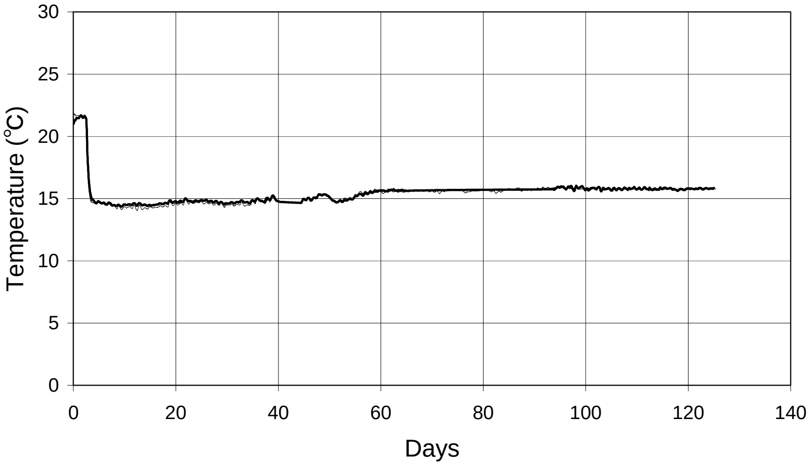


(a) Mon. Pos. 1



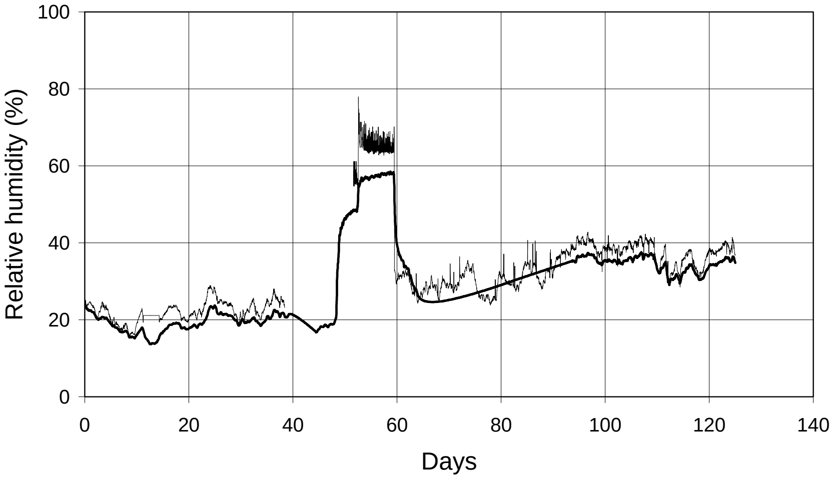
(b) Mon. Pos. 2

Figure 3-9: Temperature at different positions of Wall type B: calculation (thick lines) vs. experiment (thin lines)



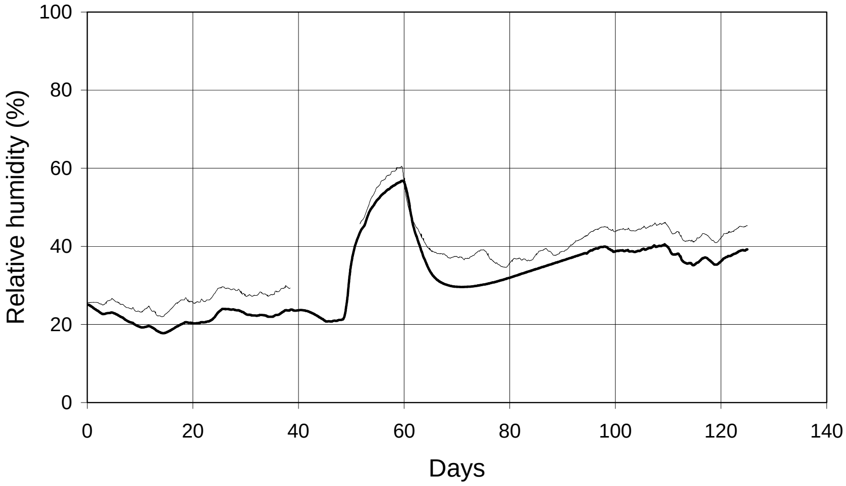
(c) Mon. Pos. 3

Figure 3-9 (cont.): Temperature at different positions of Wall type B: calculation (thick lines) vs. experiment (thin lines)

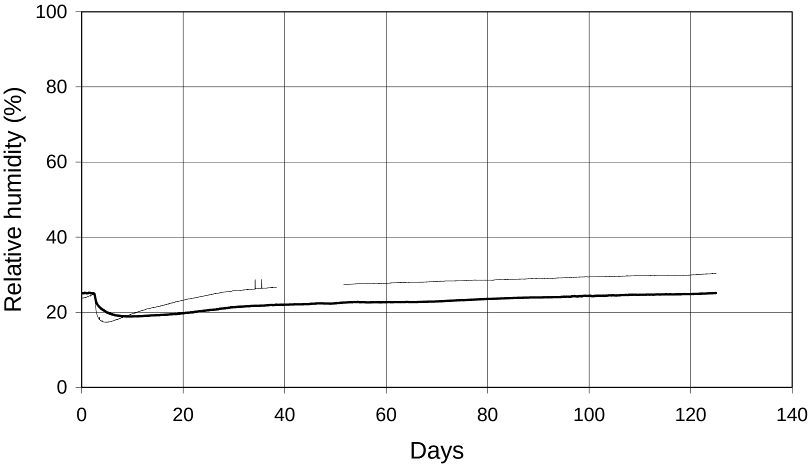


(a) Mon. Pos. 1

Figure 3-10: Relative humidity at different positions of Wall type B: calculation (thick lines) vs. experiment (thin lines)



(b) Mon. Pos. 2



(b) Mon. Pos. 3

Figure 3-10 (cont.): Relative humidity at different positions of Wall type B: calculation (thick lines) vs. experiment (thin lines)

3.4.2 Feasibility study with real climate data

Since it is necessary to test the envelope under the real climatic condition for a period of several years to assess its feasibility, numerical simulations by WUFI® program were carried out as a preliminary phase.

The climatic weather data of Kyoto (136° east longitude, 35° north latitude) was chosen as an appropriate case for the assessment. Its climate shows extreme variation throughout the year, namely very hot and humid in summer, and cold and dry in winter. The model was defined as facing north so that more critical condition could be investigated. Figure 3-11 shows the temperature, relative humidity, precipitation and solar radiation on north side respectively. These data were adapted from Expanded AMeDAS Weather Data to the WUFI® program (EI, Ltd.).

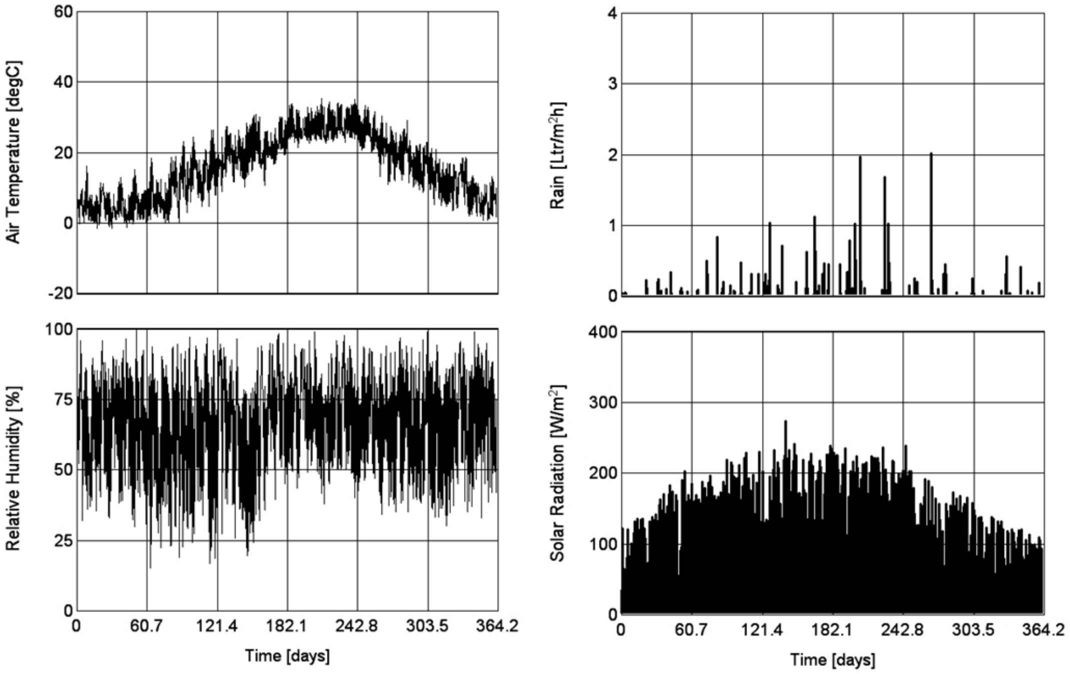


Figure 3-11: Expanded AMeDAS Weather Data of Kyoto including temperature, relative humidity, rainfall and solar radiation for a period of 1 year, repeated 3 times to get overall simulations

The same simulation models used for the validation of the climate chamber tests were considered for this assessment. In addition to the model of Wall type A, liquid water transport coefficient of wood fiber boards for suction and redistribution were defined using the conventional values given by the program. Those of suction were set at $1.0\text{x}10^{-12}$ m²/s and $8.9\text{x}10^{-11}$ m²/s, and those of redistribution were set at 1.0x10^{-9} m^2/s and 3.0x10^{-9} m^2/s with a moisture content of 17.3 kg/m^3 and 526.0 kg/m^3 respectively. As for the surface transfer coefficients, conventional values were used taking into account the influence of solar radiation and precipitation. Detailed values are shown in Table 3-3. The calculation period was set for three years to skip the influence of initial condition and to quantify the yearly accumulation of moisture. For the room side temperature, a sinusoidal function with a mean value of 21°C, amplitude of 3°C and a maximum on August 1st was chosen. The relative humidity was kept constant at a rather elevated value of 60%. The time step of one hour was determined to be appropriate.

Figure 3-12 shows the simulation results of relative humidity of monitoring position 2, which is the most critical site regarding interstitial condensation (Derome et al. 2008b). For both wall types, the highest peak of relative humidity is below 80% and the duration of the maximum moist periods is no longer than one week. This moist period is short enough to avoid mold growth (Viitanen 2010). In the case of Wall type B, the effect of convection in the external ventilation layer, which actually reduces the moisture load from the exterior side, is not described in the simulation model. This means the realistic relative humidity inside Wall type B is even lower than the result predicted in this simulation. As a result, these simulations indicate the feasibility of such wall constructions under Japanese climatic conditions, avoiding interstitial condensation and mold growth.

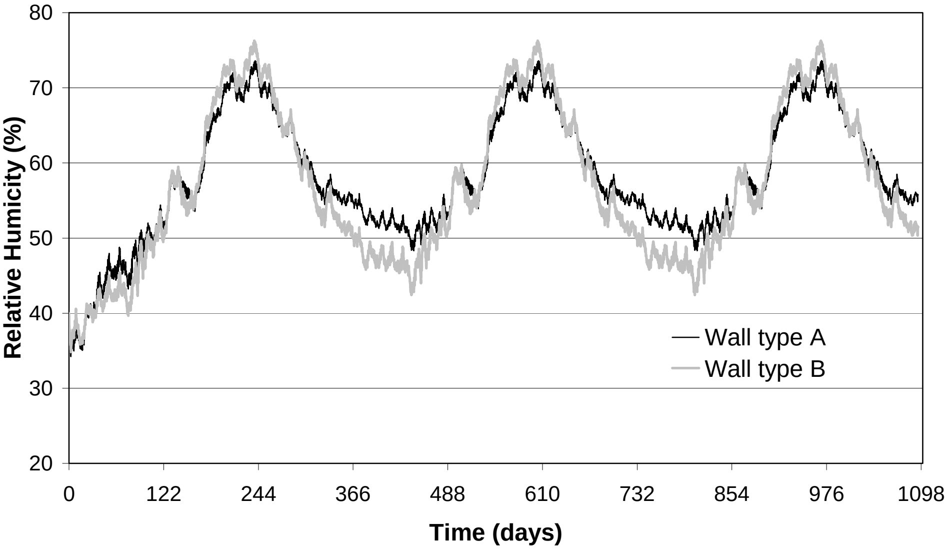


Figure 3-12: Calculated relative humidity on monitoring position 3

3.5 Conclusion

Based on the concept of sustainability, a flexible vapor-open building envelope system to be applied to subtropical regions was developed. The thermal and hygric response of two wall types were investigated by climate chamber tests, and transient heat and moisture transfer simulations. For acquiring more credible validation and ruling out sources of error, the hygrothermal properties of each material used in the walls were measured under a variety of moisture conditions. Since both measured and calculated results corresponded to each other with sufficient accuracy, it was concluded that the hygrothermal behavior of the envelope is predictable by means of the models and the simulation program used. Furthermore, for studying the feasibility of applying this envelope in Japan, simulations with real climatic data of Kyoto were carried out. It was shown that the relative humidity inside the walls did not exceed 80%, which means no risk of interstitial condensation and mold growth was predicted. The comparison between this numerical simulation and the in situ measurements, which are being planned in several test houses in Japan, will be reported in the future. Further investigations on the hygrothermal characteristics of materials when subjected to changing moisture loads such as moisture buffering functions (Rode et al. 2005) (Kwiatkowski et al. 2008), and parameter studies regarding the sensibility of the walls in terms of insulation thickness are needed.

3.6 Acknowledgement

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4 Heat and Moisture Balance Simulation of a Building with Vapor-open Envelope System for Subtropical Regions (Paper II)

Abstract

Global warming and the resource depletion induced discussions on sustainable developments within the construction sector. Also the rapid urbanization in subtropical regions is becoming one of the most important global issues. Appropriate measures must be taken in such developments to avoid further damage to the environment. In this study, the heat and moisture balance simulation of building with a sustainable building envelope system for subtropical climate was proposed. In the moisture balance simulation the moisture buffering by the interior materials was taken into account. The prediction of moisture buffer value (MBV) of the interior finishing materials was attempted and validated by measurements. Subsequently, the whole building calculation was carried out and the contribution of the moisture buffering to the indoor comfort and energy consumption was investigated. The MBVs of the mineral-based materials were predicted with high accuracy. However, that of wood-based composite was much higher than the experimental value. In order to create a more accurate model, nonlinear moisture conductance should be accounted when modeling wood-based materials. The heating and cooling demand of a test house was 9.4 kWh/m^2 and 14.5 kWh/m^2 respectively. It was concluded that the utilization of the building envelope system has a high potential to provide sustainable houses in subtropical regions. In order to enhance both energy efficiency and indoor comfort of buildings in subtropical regions, there still is a strong need to develop a holistic method to find the optimum building design considering not only moisture buffering but also all the relevant factors. The presented model will be validated by in-situ measurements in the near future.

Goto Y., Ghazi Wakili K., Frank T., Stahl T., Ostermeyer Y., Ando N., Wallbaum H.: “Heat and moisture balance simulations of a building with vapor-open envelope system for subtropical regions”. Building simulation 5(4): 301-314, 2012.

4.1 Introduction

Global warming and the resource depletion induced the discussions on sustainable developments. It is often said that sustainability comprises three pillars, namely ecological, economic and social sustainability. It has been agreed that the load of the human activities to the environment must be minimized. However, the other two aspects of the sustainability are somehow intricate to assess their real benefit to the society. Nevertheless, it is certainly needed to provide solutions in any field so that substantial measures of so-called strong sustainability can be implemented for the realization of sustainable society. Among all the sectors, construction industry is one of the most important fields since it is contributing by 50% to the greenhouse gasses emission related to the global warming and by 40% to the resource consumption on the global scale (UNEP 2003). Furthermore, many of the human activities take place in the built environments indoors. This means that the comfort and health issues, which needless to say are keys for social sustainability, are also greatly related to the quality of the buildings. Therefore buildings are no doubt one of the most important factors regarding all the aspects of sustainability.

When having an overview of the sustainable construction on global scale, there have been certain developments in terms of ecological issue in countries which have rather mild/cold climatic conditions. The important technical issues such as interstitial condensation problem and the heat balance of buildings have already been investigated, and sophisticated technologies have been implemented in the industry (for example Peper et al. 2001). At the same time, the rapid urbanization in developing countries is becoming one of the most important global issues (CIB & UNEP-IETC 2002). In order to decelerate the corresponding environmental load, appropriate measures must be taken in such developments immediately. Transferring the existing technologies from the countries with cold climatic conditions to those areas might be one of the solutions. However, there are always certain difficulties because every region has its own geographical, social and cultural background. In this sense, the adaption of the building designs to the local design conditions is of great importance. Especially when considering technology transfer from rather cold to rather warm regions, this climatic difference must be considered thoroughly. The difference of climatic condition has significant influence on the design of the building envelope and the housing services as the method to acquire the better energy efficiency and the better indoor comfort may be significantly different. In the worst case, the inappropriate building design results in damages to the building and to the health of the inhabitants (Jarvis et al. 2001). Kishi et al. reported the health problem of residents in Japan due to the dampness in buildings (Kishi et al. 2009), which is supposedly due to the lack of appropriate measures in the construction design.

Vapor-open building envelope system for subtropical regions has been presented and tested in the laboratory by the authors (Goto et al. 2011). This envelope system mainly consists of 3 layers with natural materials, namely the external insulation layer with wood fiber board, the structural layer with cross laminated wooden panel and the interior finishing layer with clay board. The basic design philosophy of this system is that the envelope consists of hygroscopic materials with moderate vapor permeability. This system allows the moisture flux to move through the wall in both directions. By defining the appropriate thickness to each layer, it is possible to avoid moisture related problems inside the wall.

It has been shown that it is possible to predict the heat and moisture transfer across the wall with given exterior and interior boundary conditions by means of a commercial simulation tool for transient heat and moisture transfer. However, there remained a fundamental problem with the setting of the model. The rigid boundary conditions on both external and internal side are unaffected by the heat and moisture release or uptake of the wall. For the external side, this is negligible because the exterior climate is not assumingly affected by such a phenomenon. While, it is of major concern for the internal side especially regarding the comfort issue. As for the heat exchange between them, it is assumed that there is not a big contribution of the interior finish to the air by heat conduction. However, the moisture exchange between them by adsorption and desorption must have a certain impact. In fact, there have been numbers of studies on the integration of moisture buffering into the building design process regarding acquiring more stable room climate and energy efficiency (for example (Padfield et al. 2004) and (Rode et al. 2008)). Chan et al. found that there is a big energy saving potential of the energy consumption for heating and cooling by implementing better quality building envelope under subtropical regions (Chan et al. 1998) and Osanyintola et al. pointed out that it is further improved especially by enhancing the moisture buffering by room interior (Osanyintola et al. 2006). In order to acquire more comfortable conditions as well as less moisture related problems in the hot and humid condition, controlling the indoor relative humidity within moderate range is one of the most important measures. While studies have been attempted in the conditions of cold regions (for example Tariku et al. 2011) and , there is a strong need to integrate the moisture transfer simulation across the building envelope and the prediction of room temperature and humidity into one heat and moisture balance simulation of the whole building which considers the subtropical climatic conditions.

In this study, the heat and moisture balance simulation of an entire built environment applied to the envelope system was proposed. Within this simulation, the moisture buffering phenomenon by the interior materials were integrated into the moisture balance simulation using moisture buffer value (MBV) proposed in (Rode et al. 2005). At the same time, the prediction of MBV of interior finishing materials was attempted using transient heat and moisture transfer model. This model was validated by the actual moisture buffering test of those materials. In the end, the whole building calculation was carried out and the contribution of the moisture buffering to the indoor comfort and energy consumption was investigated using the climatic condition of Hikone (Japan), which has a typical subtropical climatic condition, as a reference case.

4.2 The whole building simulation model

4.2.1 The overall structure of the simulation

The purpose of creating the whole building simulation model is to predict indoor air temperature and humidity. By acquiring those values, it becomes possible to assess the energy consumption, indoor comfort and the risk of condensation of the building. The simulation consists of four steps. Step 1 is the transient heat and moisture transfer simulation across the wall. In this step, the optimum layer construction, which does not have a permanent moisture accumulation in the wall, is identified by applying the actual weather data on the exterior side and a given room condition on the interior side. This method is described in (Goto et al. 2011) in detail. In Step 2, the dynamic heat balance simulation is carried out. The input for this simulation is the wall make-up which is identified in Step 1 and the parameters which have major impact on the heat transfer in the building such as the set-point temperature and ventilation rate as well as the outdoor climate. The time-dependent room temperature is calculated and this is used in Step 3, which is the simulation of moisture balance. In this dynamic moisture balance simulation, the time-dependent relative humidity of the room is predicted by introducing the moisture flow due to air exchange between the exterior and interior, internal moisture load and the moisture buffering by the interior materials. In Step 4, the predicted indoor temperature and humidity is finally used as the boundary condition of the transient simulation across the wall, which is done once with the tentative boundary indoor condition in Step 1. Once it is confirmed that there is no interstitial condensation with the predicted room condition, the optimization of the wall make-up and therefore the heat and moisture balance simulation is completed. The whole structure of the simulation is illustrated in Figure 4-1.

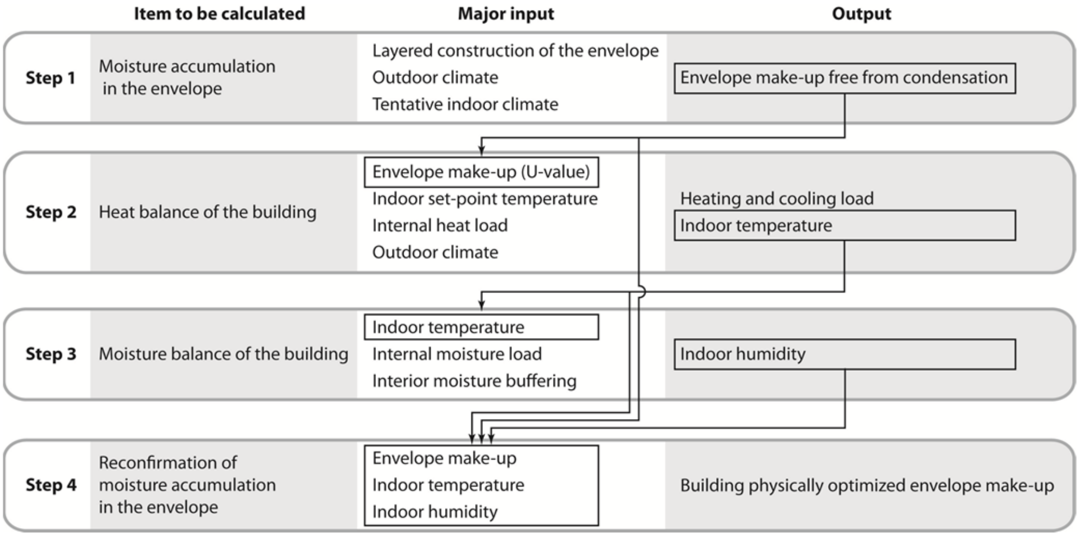


Figure 4-1: The structure of the whole building heat and moisture balance simulation

4.2.2 Heat balance simulation

The heat balance simulation of the whole building is carried out using the simulation program Helios which was developed by EMPA (Frank et al. 2006). Helios is able to perform dynamic energy simulations on hourly basis in accordance with the ISO standard "Energy performance of buildings – Calculation of energy use for space heating and cooling" (ISO 13790 2007). For the energy calculation, a one zone building model is used. The major parameters considered in the calculation are; exterior temperature, exterior humidity, solar radiation, shading around the openings, ventilation rate, heat exchange by the mechanical ventilation, air infiltration, set-point indoor temperature, indoor heat load and indoor heat buffering by the building elements as thermal mass.

The thermal property of the envelope is defined according to the actual layer design of the building by characterizing the layers with its thermal properties such as thermal conductivity and specific heat capacity. The exterior climatic condition can be imported from external data base. The openings are modeled simply based on the area of each opening, their U-value and g-value (the ratio of the sunshine transmitting through glazing). The shading of each opening are modeled based on its simplified geometry. Regarding the consideration of the user behavior, the heating and cooling set-point temperature, which may differ from one inhabitant to another, needs to be defined. As for the interaction between the solar gain and human behavior, it can be modeled that movable shading is activated when the room temperature is at a certain degree or higher. The daily schedule of the internal heat gain due to the human activities and the appliances can also be defined on hourly base.

4.2.3 Moisture balance simulation

When discussing the moisture balance of buildings, it is necessary to differentiate two major sources of moisture. One source is the exterior air. When the exterior air enters the house as the result of ventilation or infiltration, the moisture contained in the air also comes in. The other moisture source is the internal moisture load due to activities of the humans in the building such as cooking, bathing and so on. It is very important to note that this moisture generation creates humidity peaks in the buildings. A humidity peak directly affects the people's comfort and creates the peak load of the equipment for dehumidifying which actually requires an adequate design of housing services and often results in higher energy consumption. When the interior of the room is designed using hygroscopic material such as wood and clay, this humidity peak could be reduced by the sorption effect of those materials, the so-called moisture buffering effect.

In order to include moisture buffering in the moisture balance simulation of a building, it is necessary to introduce a factor representing the buffering function. There are several methods to define the characteristics of moisture buffering such as the JIS standard "Test method of adsorption/desorption efficiency for building materials to regulate an indoor humidity" (JIS A 1470-1 2002) and the ISO standard "Hygrothermal performance of building materials and products" (ISO/DIS 24353 2006). In the NORDTEST project (Rode et al. 2005), one simplified method to determine the moisture buffering property moisture buffer value (hereafter called MBV) of building materials was proposed. In the present study, MBV was chosen for expressing the moisture buffering performance of interior materials. The advantage MBV is that all materials can be compared on the same basis. Since the testing method was designed assuming the ordinary conditions of built environment within the NORDTEST protocol, the comparison of materials can be directly used when designing the interior and choosing the materials.

By using the room temperature which is calculated in the heat balance simulation, the indoor humidity is calculated by means of a simplified moisture balance equation (Zürcher et al. 2010) (equation (4-1)) which includes the factors of ventilation, internal moisture load and moisture buffering by the interior materials.

$$\left(V_R + V_{sor}\right) \cdot \frac{dc_i}{dt} = q_v \cdot \left(c_i - c_e\right) + G_{\text{int}} \tag{4-1}$$

Where V_R (m^3) is the volume of the room, V_{sor} (m^3) is the equivalent volume of air representing the sorption capacity of the interior surfaces, c_i (g/m^3) is the absolute humidity of the room, q_v (m^3/h) is the exchanged airflow rate, c_e (g/m^3) is the absolute humidity of the supply air, G_{int} (g/h) is the internal moisture load. V_{sor} is calculated by equation (4-2).

$$V_{sor} = \frac{\sum A_k \cdot MBV_k \cdot 100\% RH}{c_{i,sat}} \tag{4-2}$$

Where A (m^2) is the area of the sorption-active interior surface area, MBV (g/m^2%RH) is the moisture buffer value which was defined in the NORDTEST project (Rode et al. 2005) and $c_{i,sat}$ (g/m^3) is the absolute humidity of the room air by volume at saturation. By solving equation (4-1), the absolute humidity of the room air c_i can be given as a function of time as shown by equation (4-3).

$$c_i\left(t\right) = c_e + \frac{G_{\text{int}}}{q_v} \cdot \left(1 - e^{-\frac{n_L}{1+V_{sor}/V_R} \cdot t}\right) \tag{4-3}$$

Where n_L (1/h) is the ventilation rate.

4.3 Prediction of moisture buffering property

4.3.1 Moisture Buffering Value

Building materials are always exposed to the ambient air whose moisture content is continuously changing. The hygroscopic materials react to the change of relative humidity by adsorbing or desorbing the moisture in the air. The adsorption/desorption results in the weight change of the materials. This weight change is the index for evaluating the moisture buffering performance. In the definition of MBV, the weight change is divided by the sorption active surface area of the material and by the gradient of the relative humidity. Therefore MBV is expressed in the unit of g/(m^2•%RH). As mentioned above, the advantage of MBV is the universal use of this property within the construction industry. On the other hand, it is necessary to carry out the measurements for acquiring the value. The testing setup is rather demanding due to the special equipment which keeps the temperature and the humidity of a certain amount of air constant. For the time being, the number of materials whose MBVs have been published is limited. For practitioners who do not have the easy access to MBV equipment, this is a major lack of information. Therefore it is meaningful to establish a method to estimate the MBV with the aid of widely used simulation tools. This is expected to contribute to the building industry to save time and money to carefully investigate the moisture buffering influence on the built environment and energy consumption.

4.3.2 Moisture transfer mechanism

When discussing the property of weight change due to sorption, it is necessary to model the moisture transfer mechanism between the ambient air and the materials. In normal building materials under normal conditions, it is necessary to consider three moisture transfer mechanisms; surface emission, diffusion and capillary conduction. All of those properties are different from one material to another. In order to predict the MBV, it is definitely necessary to identify the parameters which are most relevant to the moisture buffering property. In the following these parameters are discussed.

4.3.2.1 Surface emission

Surface emission is characterized by the resistance when the moisture moves from the material surface to the surrounding air. It is called surface emission coefficient S. Because this is a convective transfer, the corresponding moisture transfer resistance decreases with increasing velocity of the ambient air. Hence, this parameter is dependent not only on the material characteristics but also on the micro structure of the surface, which could have a significant influence on the micro-scale air flow. In the conventional methods, S is acquired only by measurements which have a certain surface structure of the material and certain flow of the ambient air, which means that the S value is only valid within the measurement conditions. In this case, the measurement setup should not be largely different from the indoor air flow condition. There also have been attempts to define a model which is able to predict this convective moisture transfer without using the S value. Defraeye et al. created a conjugate model that can take into account the spatial and temporal variability of S, which is determined a posteriori in the model (Defraeye et al. 2012). However the calculation model itself is not easy to deal with on the practical level yet.

4.3.2.2 Diffusion

Diffusion is characterized by two mechanisms in the material, namely vapor diffusion and surface diffusion. Vapor diffusion occurs through the pores and micro capillaries in the material. Its driving force is the gradient of the vapor pressure. The phenomenon is generally described by Fick's law of diffusion. When discussing the vapor diffusion through building materials which have micro pores, Fick's diffusion is not actually applicable to describe the diffusion phenomenon because the collisions between molecules and the inner surface of the material occurs more often than those between molecules themselves. This transport mechanism is called Knudsen transport. The Knudsen number determines whether statistical mechanics or the continuum mechanics formulation of fluid dynamics has to be used: If its value K_n is near or greater than one, the mean free path of a molecule is comparable to a length scale of the problem, and the continuum assumption of fluid mechanics is no longer a good approximation. In this case statistical methods have to be considered. However, when the normal conditions which are covered in building physics are applied, the resistance against the diffusion is given by dividing the water vapor diffusion coefficient in air by water vapor diffusion resistance factor μ. By introducing μ, Knudsen transport can also be modeled in the similar way as Fick's diffusion (Gertis 1976). Therefore it is significant to give the appropriate μ value of the material when modeling vapor diffusion within the simulations of porous building materials.

The other one is surface diffusion. This is the diffusions of the water molecule which is accumulated on the inner surface of the material. Relative humidity can be used as the driving potential when describing this mechanism by Fick's law (Künzel 1995). When discussing the moisture buffering of a material due to moisture transport, this diffusion is less important since the transfer of the accumulated water does not give the weight change. However, this needs to be taken into account in the overall transfer model because all the moisture transports driven by the same potential are dependent on each other and cannot be separated from the whole system.

4.3.2.3 Capillary conduction

Capillary conduction happens when the micro capillaries are filled with liquid water. This accumulation is often called capillary condensation. The transport of this water is described by means of Hagen-Poiseuille law. It was reported that this law can be approximated by Fick's diffusion equation by introducing the capillary transport coefficient which depends on the water content of the material (Crank 1975). Relative humidity is widely used as the driving potential to describe the transport mechanics.

4.3.3 The relevant parameters to model moisture buffering

As shown above, the moisture transfer mechanisms which are relevant to building materials can be modeled by diffusion law. In fact several studies have been done to predict the sorption behavior of materials using Fick's diffusion model. Wadso et al. measured the sorption property of soft wood by the decently designed apparatus (Wadso 1993a and 1993b), and one of the results was that the diffusion coefficient gained within the measurements using dynamic change of humidity condition was much lower than the literature values which were gained under steady state conditions. Shi carried out the analyses of the sorption behavior of wood fiber board and wood fiber-based composites using a nonlinear curve fitting algorithm method (Shi 2007). This was the attempt to fit the Fickian model curve to the measured weight change curve by changing the parameters, namely the moisture diffusion coefficient and the surface emission coefficient. Consequently it was shown that even though Fickian diffusion may not exactly model the actual sorption behavior, it was possible to reproduce the measured curve roughly, which is actually good enough to calculate the MBV. Those studies give an important indication that as far as Fick's diffusion model is concerned, the fitting of the curve can be achieved by controlling the value of diffusion coefficient and surface emission coefficient.

In the present study, the Fickian model was assumed to be sufficient to model the adsorption/desorption process in order to predict the weight change. The general goal of this study was to establish the holistic designing method of the wall make-up and the whole building being free from any experimental processes. It must be clearly noted that it was not aimed to develop a highly sophisticated model but rather to establish the method with which the MBVs of building materials can be roughly estimated.

4.3.4 Simulation tool

In order to carry out a reliable modeling of moisture buffering within the protocol of NORDTEST, it is necessary to employ a suitable simulation tool. The complexity of the model depends on the tools, but it is reasonable that the model is able to deal with the simultaneous heat and moisture transfer. Even though NORDTEST is performed in isothermal situation, the energy which are relevant to both heat and moisture transfer such as latent heat should be taken into account for achieving more reliable simulations. As for the geometry of the model, one dimensional model is enough because only one side of the test specimen is exposed to the air with humidity steps.

Numbers of simulation tools to carry out the one dimensional transient heat and moisture transfer through multi-layered building components have been developed and some of them are available commercially (for example MATCH 1.6.0.5 (Bygge- og Miljoteknik 2003) and 1D-HAM (Hagentoft et al. 2000). WUFI Pro 5.1® is one of those tools (Fraunhofer-Institute for Building Physics 2011). The materials can be modeled by giving its thickness, bulk density in dry condition, porosity, moisture-dependent thermal conductivity, moisture storage function (sorption isotherm), moisture dependent vapor diffusion resistance factor (μ), specific heat capacity and liquid transport coefficient for suction and redistribution. In addition to those material properties, the surface emission resistance can be introduced by considering S_d-value which is the equivalent air layer thickness in terms of diffusion resistance.

The coupled differential equation of heat and moisture transport used in WUFI is given in equation (4-4) and (4-5) (Künzel 1995).

$$\frac{dH}{d\theta}\cdot\frac{\partial\theta}{\partial t}=\nabla\cdot\left(\lambda\nabla\theta\right)+h_v\nabla\cdot\left(\delta_p\nabla\left(\varphi p_{sat}\right)\right) \tag{4-4}$$

$$\frac{dw}{d\varphi}\cdot\frac{\partial\varphi}{\partial t}=\nabla\cdot\left(D_\varphi\nabla\varphi+\delta_p\nabla\left(\varphi p_{sat}\right)\right) \tag{4-5}$$

Where $dH/d\theta$ (J/m^{3}K) is heat storage capacity of the material, $dw/d\varphi$ (kg/m^3) is its moisture storage capacity of the building material, λ (W/mK) is its thermal conductivity, D_φ (kg/ms) is its liquid transport coefficient, δ_p (kg/msPa) is its water vapor permeability, h_v (J/kg) is evaporation enthalpy of water, p_{sat} (Pa) is water vapor saturation pressure, θ (°C) is temperature and φ (-) is relative humidity. In the calculation of WUFI Pro 5.1®, those differential equations are dealt as one dimensional heat and mass transfer.

As for the modeling of each moisture transport mechanism explained in 4.3.2.2, the resistance against vapor diffusion is given by μ. Also it should be noted that surface diffusion and capillary conduction are combined and described by the Fickian diffusion using relative humidity as the driving potential where the resistance factor is given by liquid transport coefficient D_φ.

4.3.5 Measurements of MBV

4.3.5.1 Test specimen

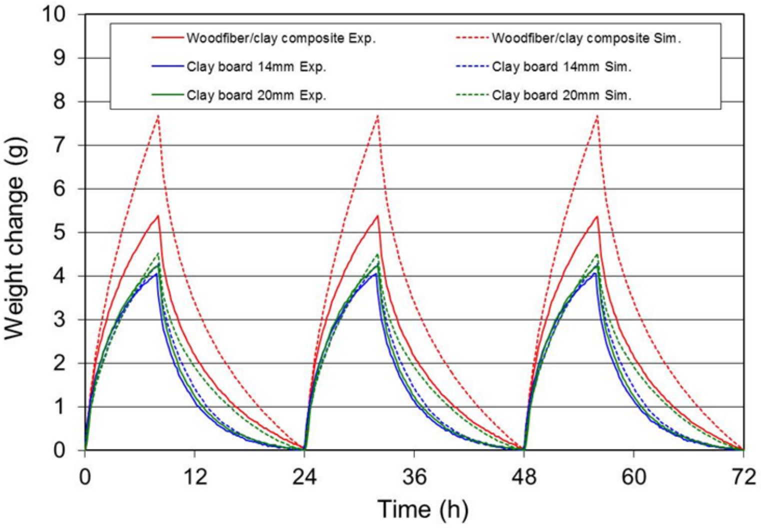
The interior finishing materials were chosen according to the design philosophy of the envelope system, which means the materials must be hygroscopic, natural and contain no toxic substances. Two materials were identified, namely a clay board and a composite of wood fiber and clay. The clay specimens were prepared with two thicknesses (14 mm and 20 mm) with the same composition of the ingredients. The thickness of the wood fiber/clay composite was 20 mm. Those boards were cut into 250 mm x 250 mm square shaped specimens. In order to investigate the more realistic MBV, the boards with surface finishing were also considered. This 8 mm thick finishing was done with fine clay plaster which consists of several layers in accordance with the conventional plastering work including the surface painting. All surfaces of each board except the one which was exposed to the ambient air were coated by wax and sealed with aluminum tape so that no moisture uptake/release did happen through those surfaces. The specimens were seasoned in a climatic chamber under 23 °C and 50 %RH preliminary to the measurements.

4.3.5.2 NORDTEST

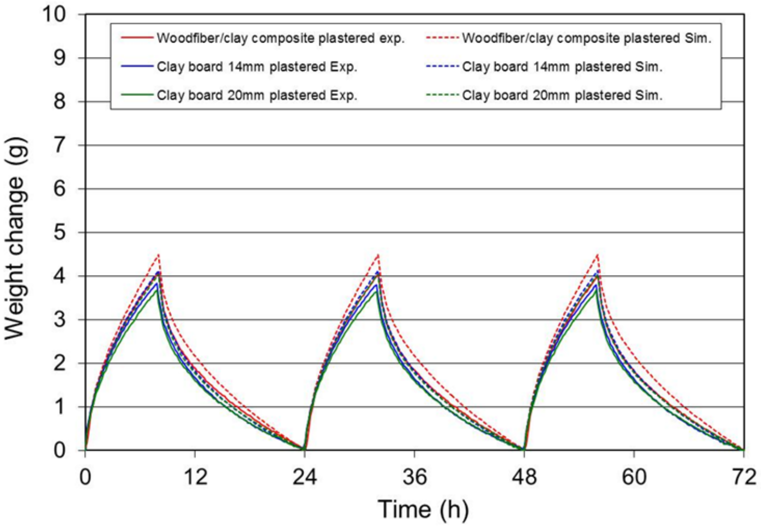
The MBV measurement was performed in a chamber (Feutron® Typ3523/16 Feutron Klimasimulation GmbH). In this chamber each material was exposed to the periodic change of the relative humidity, namely 8 hours at 75%RH and 16 hours at 33%RH and both at 23 °C. This condition was in accordance with the NORDTEST protocol which assumes to be representing the actual moisture situation of rooms of normal residential buildings taking into account the human activities. The air inside the chamber was continuously circulated so that there was no humidity gradient in the air. The weight of the specimen was measured every 12 minutes automatically. The agitation of the air was stopped at the weighting time so that the air flow did not disturb the measurement. The measurements were finished when the difference of the weight change within one cycle (24 hours) was within 5% difference in the last three cycles in a row. The measured weight change curve is shown in Figure 4-2 and gained MBVs are listed in Table 4-1.

Table 4-1: Measured and predicted MBV

	Moisture Buffer Value (MBV) (g/m^2%RH)					
	Clay board 14mm	Clay board 20mm	Woodfiber/Clay composite	Clay board 14mm plastered	Clay board 20mm plastered	Woodfiber/Clay composite plastered
Experiment	1.55	1.62	2.05	1.46	1.40	1.56
Simulation	1.63	1.72	2.92	1.57	1.54	1.76



(a) Non-plastered specimens



(b) Plastered specimens

Figure 4-2: Experiment and simulation result of NORDTEST: a) Non-plastered specimens, b) Plastered specimens

4.3.6 Numerical simulation

The models corresponding to the measurements described above were created for the following materials: clay board of 14 mm thick, clay board of 20 mm thick, wood fiber/clay composite of 20 mm thick and the corresponding plastered boards of each type. In order to carry out more reliable simulations, the following material properties were measured; density in dry condition, thermal conductivity at different humidity conditions (0 and 80%RH), water vapor diffusion resistance factor at different humidity conditions (15, 25, 40, 71.5 and 86.5%RH, 23 °C) and equilibrium moisture content at different humidity conditions (0, 30, 50 and 90%RH, 23 °C). Porosity and specific heat capacity were taken from the database (Fraunhofer-Institute for Building Physics 2011) since those are assumingly not much relevant to the simulation result as long as NORDTEST is concerned. As for the plaster which was put on those materials, only the water vapor diffusion resistance factor was measured. The other parameters were taken from the abovementioned database. Those parameters are listed in Table 4-2.

The geometry of the model of plastered clay board of 20 mm is shown in Figure 4-3 as an example. The S_d-value of the surface of the plaster was tentatively given at 0m. The other side of the specimen was modeled to be covered with an impermeable membrane with the S_d-value of 1500 m because the specimen was sealed so that no moisture transfer was allowed. The heat resistance of each surface was set at 0.125 m^{2}K/W, which is the conventional value for indoor partition wall.

The initial conditions for the simulation was set at 23°C and 50%RH as the specimens for the NORDTEST were seasoned under this condition preliminary to the measurement. As a preliminary simulation, the simulation with the boundary condition which was extracted from the measurement (the measured temperature and the relative humidity) and the simulation with the designed boundary condition which merely reproduces the designed humidity jump were compared to each other. The result of those simulations corresponded to each other with a very high accuracy. Therefore the climatic condition in the actual simulations was given by the designed condition. The predicted weight change is shown in Figure 4-2 and predicted MBV is listed in Table 4-1.

Table 4-2: Input parameters for the NORDTEST simulations

	Bulk Density	Porosity	Specific heat capacity	Thermal conductivity		Water vapor diffusion resistance factor μ					Equilibrium moisture content				
	kg/m^3	m^3/m^3	J/kgK	W/mK		-					kg/m^3				
				RH 0%	RH 80%	RH 15%	RH 25%	RH 40%	RH 71.5%	RH 86.5%	RH 0%	RH 30%	RH 50%	RH 90%	RH 100%
Clay board	1438	0.6	1500	0.30	0.49	7.6	8.7	8.1	7.2	6.1	0.0	6.26	8.42	16.85	300
Woodfiber/clay composite	495	0.88	1500	0.06	0.07	5.1	6.7	5.6	5.7	5.7	0.0	15.4	20.9	52.3	300
Clay plaster	1514	0.42	1000	0.59	1.63	15.2 /11.3 (clay board/composite)					0	6.0	10.0	25.4	294

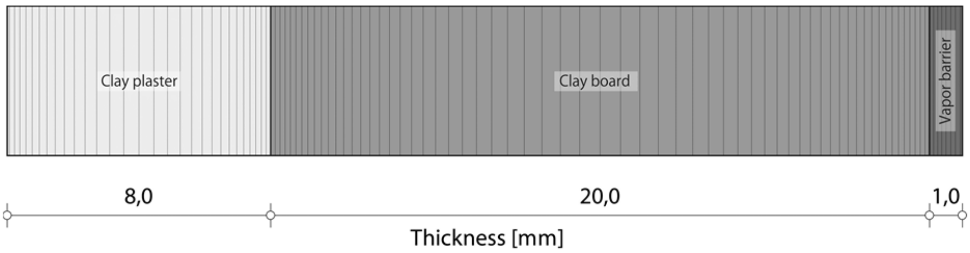


Figure 4-3: Geometry and mesh division of the simulation models for NORDTEST

4.3.7 Comparison of the measurement and the prediction of MBV

As shown in Figure 4-2(a), the experimental moisture buffering property of clay boards did not show the difference due to the thickness difference. This was because the thinner board (14 mm) was already thicker than the thickness of the sorption active part (generally called “penetration depth”). The prediction of the MBV of those boards was achieved with high accuracy. Regarding the MBV prediction of wood fiber/clay composite, the calculated value was 42% higher than the experimental value. It is assumed that wood fiber has a certain influence on this slower reaction to the moisture adsorption/desorption. Compared to mineral-based materials, which have been examined their buffering property by numerical means more or less successfully (for example (Roels 2008)), wood and wood based materials are difficult to model due to the “retarded sorption” effect resulting from its complex cell wall structure. Håkansson conducted extensive analyses on the sorption property of thin wood samples by experimental and numerical investigations based on modified Fickian approach (Håkansson 1998). It was shown that the prediction of sorption property was achieved rather accurately when internal nodes, which represent the nonlinear conductance taking into account the hysteresis, were introduced in the conventional Fickian model. Since this internal nonlinear conductance could not be modeled within WUFI® program, the simulation shows by far faster moisture uptake which results in the higher MBV value. It is suggested that experimental values shall be used for moisture balance simulations when modeling the moisture buffering by woods or wood-based materials unless models which can take into account the nonlinear moisture conductance are available. The finite difference model considering the hysteresis suggested by Korjenic et al. (Korjenic et al. 2011) might be one of potential methods to model the non-linear behavior.

Nevertheless, it should be still possible to roughly reproduce the moisture buffering performance of the wood fiber/clay composite by WUFI® simulation using arbitrary parameters as explained in 4.3.3. Therefore simulations with higher water vapor diffusion resistance factor μ, higher S_d-value which represents the lower surface emission coefficient and lower equilibrium moisture content were carried out as a parametric study. The same MBV as the actual measurement was gained when μ was set at 14.1 (240% of the measured value), when S_d-value was set at 0.018 m and when the equilibrium moisture content was reduced by 62% respectively. Figure 4-4 shows the predicted moisture buffering curves of those together with the experimental result. The arbitrary change of μ gave the best fit to the empirical data. On the other hand, that of S_d-value did not give the fit to the measured curve. This gives potential indication of how to roughly model the moisture buffering properties of wood and wood-based materials, which simply focuses on μ only. More holistic studies with more variety of wood-based materials might give a standardized method of predicting the MBV.

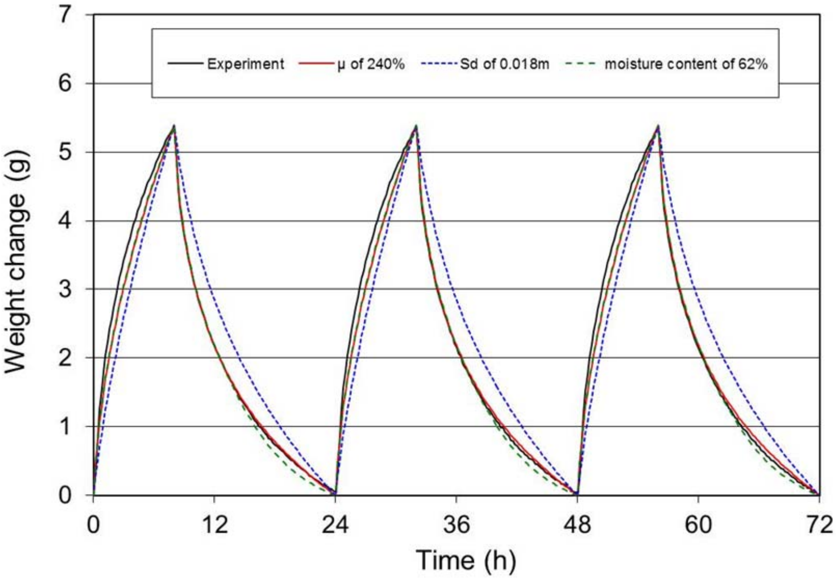


Figure 4-4: The prediction of moisture buffering performance of the wood fiber/clay composite by arbitrary changes of moisture transfer parameters

Figure 4-2(b) shows that the moisture buffering performance of all the plastered samples was more or less the same, which means that the clay plaster was thicker than the moisture penetration depth. The prediction was more or less successful. This result indicated that it is very important to carefully choose the interior finishing material and its thickness in order to make use of the buffering property of the base material. When the thickness of the surface finishing is thicker than its penetration depth, the moisture buffering performance is defined by this surface material. On the other hand, when it is thinner than its penetration depth, the base material would contribute to the overall buffering performance. An additional simulation of the wood fiber/clay composite with a plaster which has the same material property but is 3 mm thick (less moisture capacity and lower diffusion resistance than the original thickness 8 mm) was conducted. It was shown that this system has a better buffering performance compared to the 8mm plastered one by 67.8% because the whole interior finishing system was enhanced by the buffering performance of the wood fiber/clay composite which has better property than the plaster under the NORDTEST condition. The simulation result is shown in Figure 4-5. This is an important indication of future material and wall system development when trying to enhance the indoor moisture buffering.

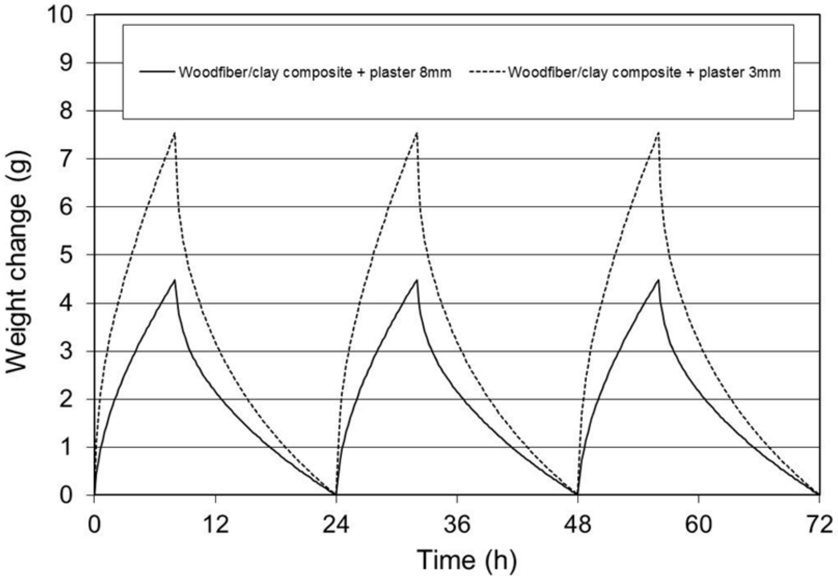


Figure 4-5: The difference of buffering performance due to the thickness difference of the plaster

4.4 Heat and moisture balance simulation of a whole building

4.4.1 Example case

Within this project, several test houses are planned to be built in central Japan whose climatic condition is subtropical. In the present study, one of those test houses with a floor area of 58.7 m^2 (hereafter called "Test House") was chosen for carrying out the in-situ measurement of the room climate (Figure 4-6). Test House will be located in Ohmihachiman city, and actual inhabitants (two adults) will be living in it. The wall make-up consists of external finishing with wooden cladding, 18 mm thick air layer, 180 mm thick wood fiber insulation, wind-tight and vapor-open membrane, structural wooden panel, 14 mm thick clay board and thin layer of plaster as interior finishing.

Figure 4-6: Test House (upper left: floor plan of the 1st floor, lower left: floor plan of the ground floor, upper right: south façade, lower right: east façade)

4.4.2 Heat and moisture balance simulation

The heat and moisture balance simulations were carried out in accordance with the methods described in 4.2.

As for the heat balance simulation, the whole building was modeled as one volume. The U-value of the wall and roof was 0.20 W/m^{2}K and that of the windows was 1.3-1.5 W/m^{2}K. The heat storage by the interior material (for example the interior finishing with clay board and clay plaster) was taken into account by giving its area and heat capacity. The heating and cooling set-point temperature was set at 20°C (maximum heating power: 3.0 kW) and 27°C (maximum cooling power: 1.5 kW). Regarding the solar gains, it was modeled so that a movable shading was activated when the room temperature reached 25°C or higher. The daily schedule of the internal heat gain due to the human activities and the appliances were defined in accordance with the Japanese guideline of energy consumption calculation (IBEC 2009). The difference of the occupation and human activities between weekdays and weekend was considered. The weekly schedule is shown in Figure 4-7. Regarding the ventilation, the mechanical ventilation with heat recovery was translated into a reduction of ventilation rate considering the actual efficiency of the heat exchanger. The input of the modified ventilation rate was 0.14 (1/h). The climatic conditions at this site were generated with METEONORM 6.1 (©Meteotest, Bern, 2010) for Hikone city where there is the nearest weather station around Ohmihachiman city (at latitude 35.2 degree north and longitude 136.1 degree east). Its temperature and absolute humidity is shown in Figure 4-8.

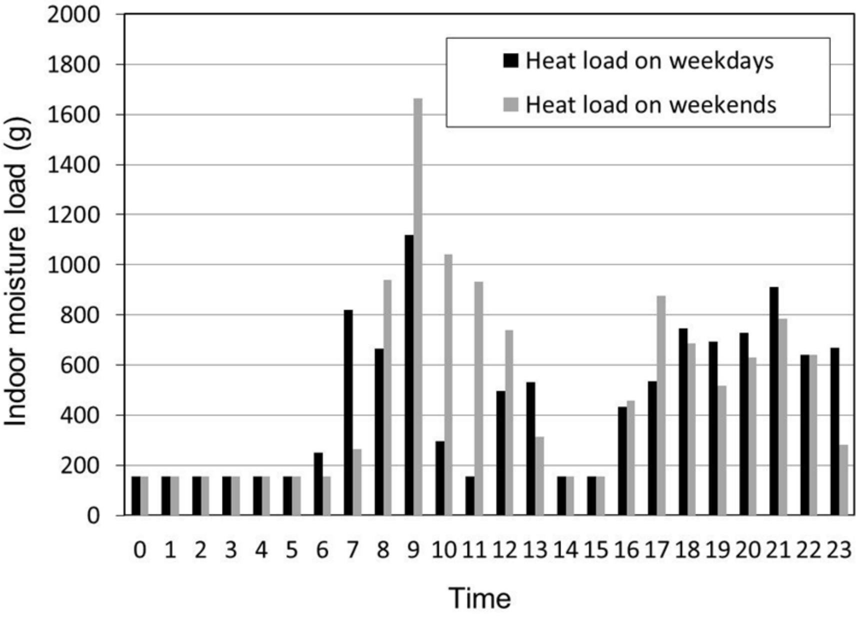
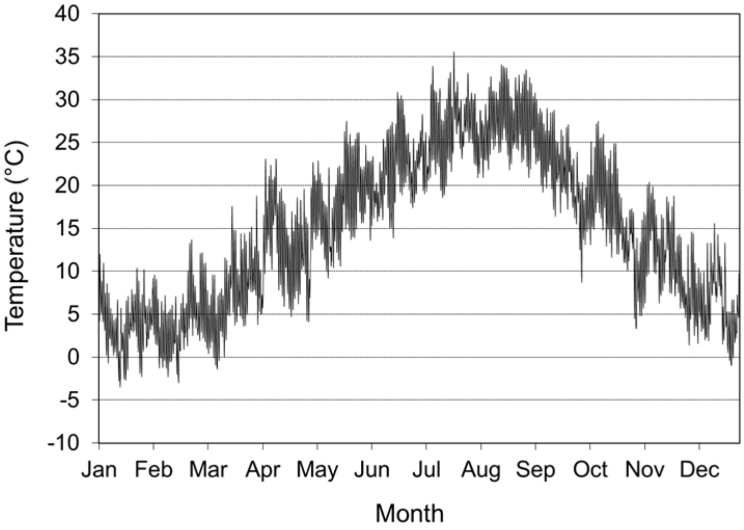
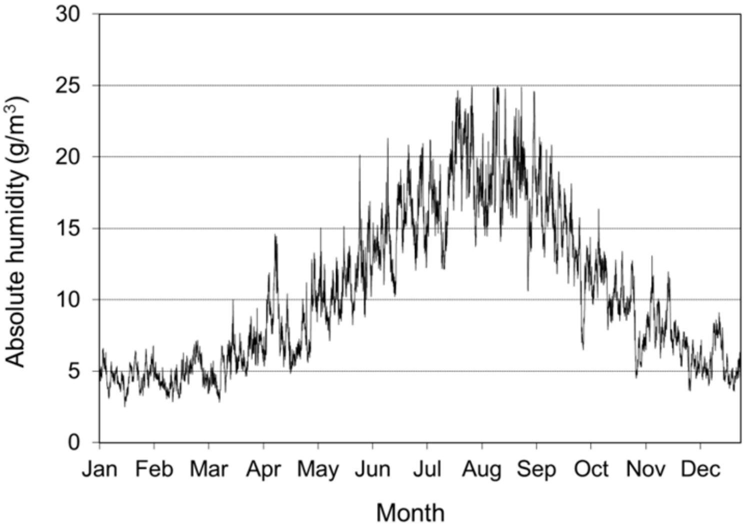


Figure 4-7: The weekly schedule of indoor heat load



(a) Temperature



(b) Absolute humidity

Figure 4-8: Climatic condition of Hikone-City throughout a year: a) Temperature, b) Absolute humidity

Regarding the moisture balance simulation taking into account the moisture buffering by interior materials, two MBVs were used. One was the MBV of untreated softwood which covers the large percentage of the ceiling (26.0 m^2). The actual experimental MBV was 1.2 g/m^2%RH which is given in (Rode et al. 2005) as the value of untreated spruce wood. The other one was the MBV of the finishing of the walls with the clay board of 14 mm thick and the plaster of 8 mm thick (24.7 m^2). The actual predicted MBV of this was 1.57 g/m^2%RH. The temperature dependency of MBV of each material was disregarded (the inputs were constant). The internal moisture load of the living room was defined according to the inhabitants' occupancy and activities based on the literature (IBEC 2009). The weekly schedule is shown in Fig.4-9. The supply air flow rate was 50 m^3/h. For taking into account the dehumidification in summer, the moisture load due to the supply air was reduced assuming a radiator type dehumidifier with the surface area of 4.6 m^2, which is actually planned to be installed. It was modeled that this equipment was activated giving the surface temperature of 18°C when the room air was 25°C or higher. *(The more detailed inputs are presented in Appendix B.)*

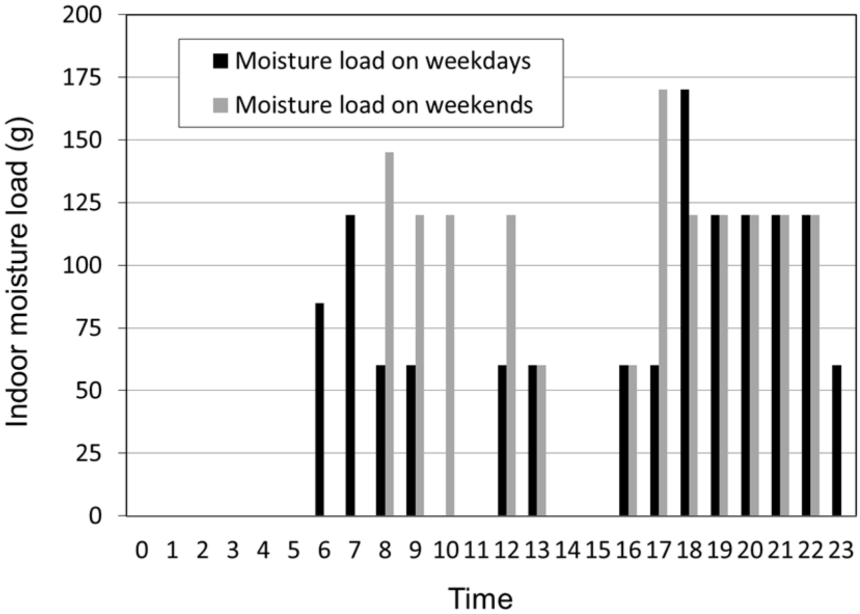
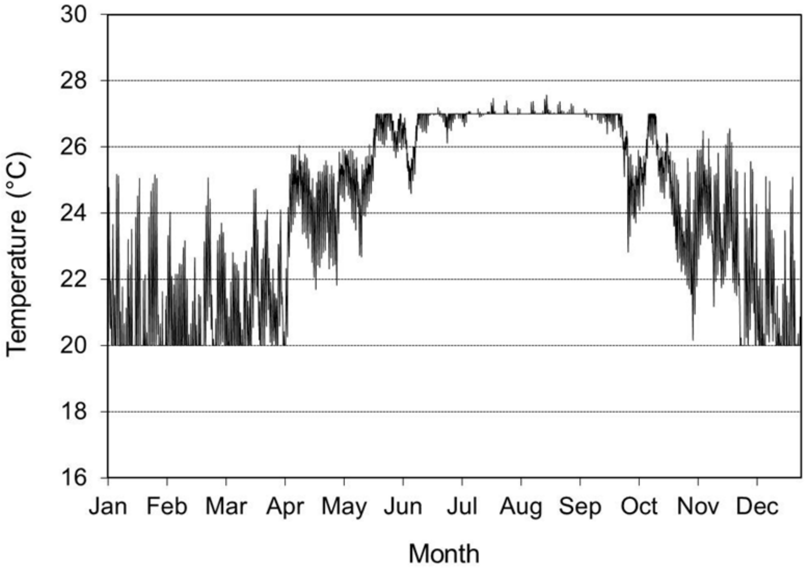


Figure 4-9: The weekly schedule of indoor moisture load of the living room

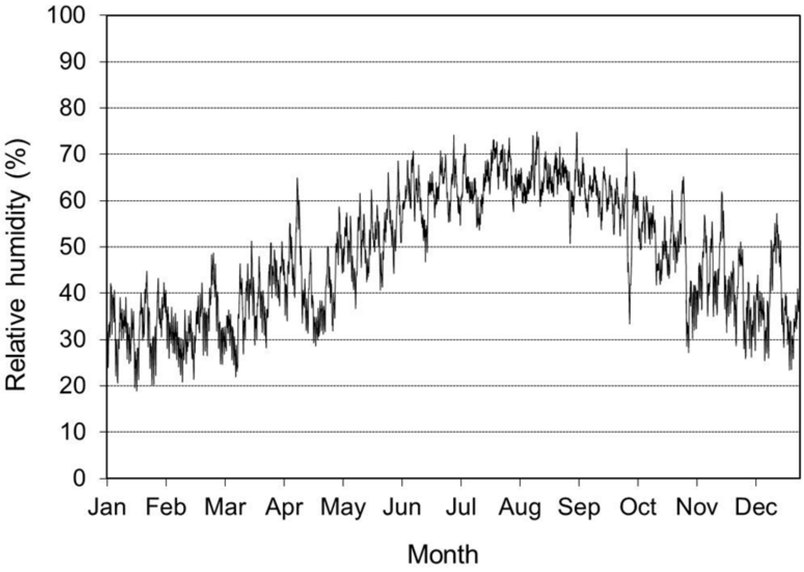
4.4.3 Results

The result of the heating and cooling energy demand was 9.4 kWh/m^2 and 14.5 kWh/m^2 respectively. The predicted interior temperature and the relative humidity of the living room which took into account the moisture buffering throughout the year is shown in Figure 4-10. In order to clarify the effect of moisture buffering, the relative humidity was calculated in two cases, namely one case which takes into account the moisture buffering by the interior and the other case which does not. Those results in a humid period (from 22.08 to 01.09) are shown in Figure 4-11.



(a) Temperature

Figure 4-10: Predicted room climate: a) Temperature, b) Relative humidity of the living room



(b) Relative humidity of the living room

Figure 4-10 (cont.): Predicted room climate: a) Temperature, b) Relative humidity of the living room

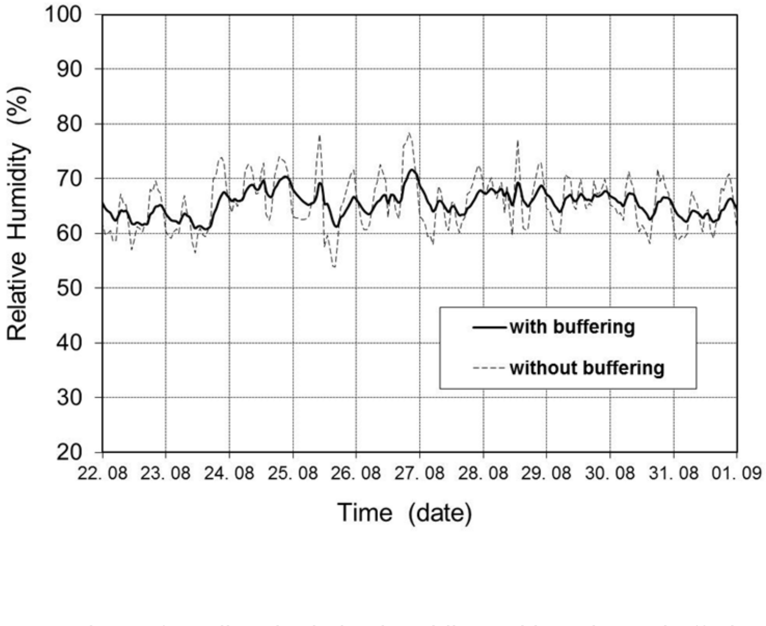


Figure 4-11: Comparison of predicted relative humidity: “with moisture buffering” vs. “without moisture buffering”

4.5 Discussion

The energy consumption for both heating and cooling was low enough compared to the other advanced standards such as Passivhaus standard (Passivhaus Institut, heating load lower than 15 kWh/m^2) and MINERGIE-P$^®$ standard (MINERGIE$^®$ Building Agency, heating load lower than around 20 kWh/m^2). This is because of the sufficient amount of the insulation and the design considering the solar gains in winter. Slight overheating in summer was observed (the room temperature exceeded the set-point cooling temperature) even though the shading system was activated. Therefore it is assumed that the interior heat load due to the appliances and human activities have a certain influence on it. No energy consumption for dehumidification was accounted within this calculation method because the radiators were activated in summer with cold water circulation. The condensation on the radiators did not cause additional energy consumption except the one for operating the water circulation.

In Figure 4-11 it is shown that the moisture buffering by the interior finishing reduced the humidity fluctuations. According to (Fang et al. 1998), the indoor air quality can be defined with an acceptability-index (Acc.), based on the air temperature, humidity and the pollution level. Acc. is given between 1.0 and -1.0. The higher the value, the more comfortable is the air. Figure 4-12 shows the predicted acceptability-index in the living room throughout the year for clean air (no CO_2 concentration or contamination by hazardous gasses). Figure 4-13 shows the comparison with the two cases, namely with and without buffering. The mean values of the Acc. did not change with the buffering function. However, it is worth noting that the fluctuation of the Acc. was reduced significantly.

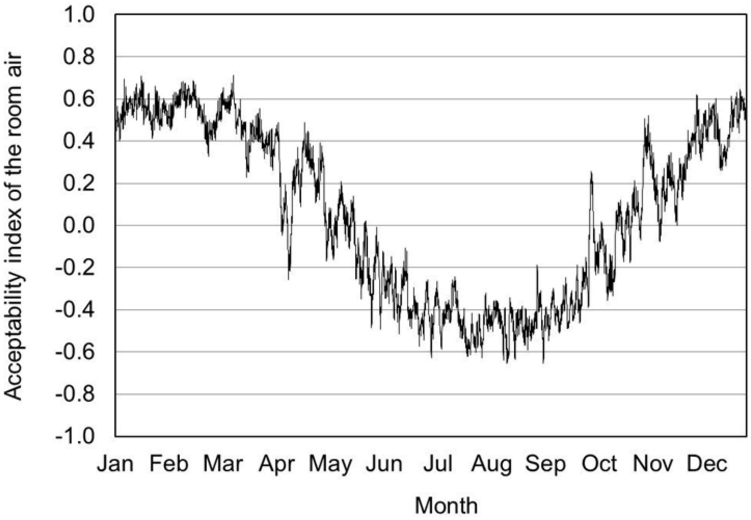


Figure 4-12: Air acceptability index of living room throughout a year

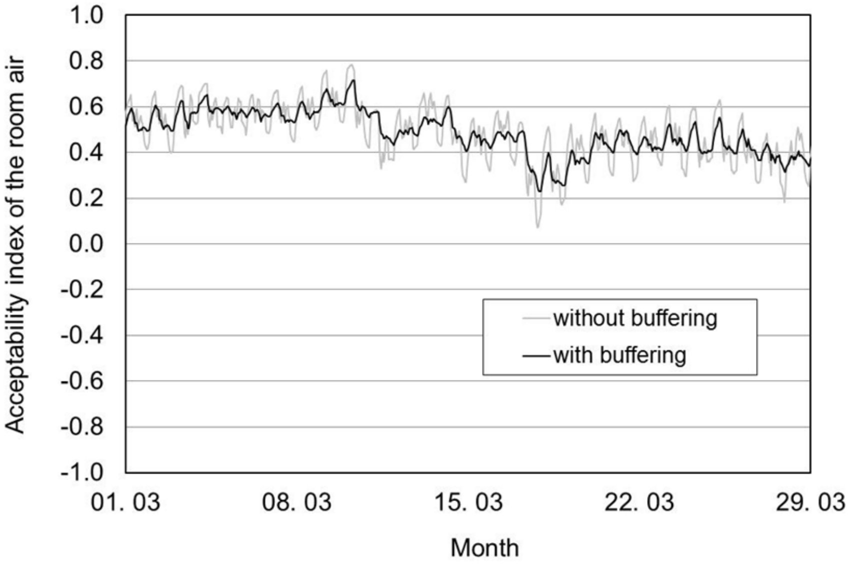


Figure 4-13: Comparison air acceptability index: "with moisture buffering" vs. "without moisture buffering"

Apparently there is a substantial potential to improve the Acc. in summer. However, there is a fundamental trade-off between the energy consumption and the Acc. It is obvious that giving lower set-point temperature for cooling would result in the better Acc. but at the same time in higher cooling energy consumption. Also introducing mechanical dehumidification would result in the similar result. The important point is that there is a strong need to find the optimum for maximizing the benefit and minimizing the environmental load due to those measures. The possible parameters to be taken account are set-point temperature for heating and cooling, mechanical dehumidification, criteria for the activation of shading, mechanical ventilation and optimal insulation thickness with regard to energy consumption. Because those factors are dependent on each other in terms of creating indoor comfort and energy consumption, there is a strong need to develop a holistic method to find the optimum building design considering all those parameters.

In order to confirm the validity of the use of the predicted MBV, an additional parametric study was conducted. The same calculation was carried out using the measured MBV of the plastered 14 mm clay board (1.46 g/m^2%RH) and its result was compared to the result presented above. The difference between the predicted relative humidity of the living room was 0.9% at a maximum.

In the end, the transient heat moisture transfer simulation across the envelope described in (Goto et al. 2011) was carried out using the temperature and the humidity obtained by this heat and moisture balance simulation. The result showed that there was no interstitial condensation inside the envelope. As a result, it was concluded that the utilization of the building envelope system introduced in this study has a high potential to provide the low-energy-consuming and durable houses in subtropical regions. The present model will be validated by the in-situ measurement in Test House in the near future.

4.6 Conclusion

In this study, the heat and moisture balance simulation of building with the sustainable building envelope for subtropical climate was proposed. In the moisture balance simulation the moisture buffering by the interior materials was taken into account. The prediction of MBV of the interior finishing materials was attempted using transient heat and moisture transfer model. This model was validated by the actual moisture buffering test of those materials. In the end, the whole building calculation was carried out and the contribution of the moisture buffering to the indoor comfort and energy consumption was investigated using the climatic condition of Hikone as a reference case.

Following conclusions were made:

1. The MBVs of the clay board and the ones with clay plaster were predicted with high accuracy. However, that of wood fiber/clay composite was 42% higher than the experimental value. It is suggested that experimental values shall be used for moisture balance simulations when modeling the moisture buffering by woods or wood-based materials unless models which can take into account the nonlinear moisture conductance are available.
2. It was indicated that the moisture buffering properties of wood and wood-based materials might be modeled with Fickian model in which modified vapor diffusion resistance is applied. More holistic studies with more variety of wood-based materials might give a standardized method of predicting the MBV.
3. When designing the interior finishing enhancing its moisture buffering performance, the system within the penetration depth should be carefully designed.
4. The heating and cooling energy demand of the Test House was 9.4 kWh/m^2 and 14.5 kWh/m^2 respectively, which were fairly low. No energy consumption for dehumidification was accounted because of the radiator-based dehumidification strategy.
5. The moisture buffering significantly contributed to the reduction of the relative humidity fluctuation. This also resulted in more stable air acceptability index.
6. In order to enhance both energy efficiency and indoor comfort, there is a strong need to develop a holistic method to find the optimum building design considering design measures, whose performance are dependent on each other, such as set-point temperature for heating and cooling, mechanical dehumidification, criteria for the activation of shading, mechanical ventilation, insulation thickness and so on.
7. From the findings mentioned above, it was concluded that the utilization of the building envelope system introduced in this study has a high potential to provide the low-energy-

consuming and durable houses in subtropical regions. The present model will be validated by the in-situ measurement in Test House in the near future.

4.7 Acknowledgement

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5 Economic, Ecological and Thermo-hygric Optimization of a Vapor-open Envelope for Subtropical Climates (Paper III)

Abstract

With regard to resource depletion and global climate change, it is becoming important to take holistic measures comprising ecological, economic and social aspects of the construction industry. An optimization method that deals with the trade-off among those pillars is needed to approach the overall life span of constructions from a holistic viewpoint. In this study, the insulation thickness of a vapor-open envelope system for subtropical regions with social advantages was investigated by an economic and ecological optimization model, taking into account both initial and running costs under the conditions of 8 cities in Japan. The thermo-hygric minimum thickness was also determined in order to ensure the longevity of the buildings. The following main findings were made: 1) the ecological optimal thickness was larger than the economic optimal thickness, 2) the thermo-hygric minimum was within the economic optimal range in most of the cases, and 3) the interest rate of the currency and the electricity price increase have a significant influence on the result of the optimization analysis. With the aid of the optimization model, it was shown that application of the envelope system is feasible in Japan, especially in the central and southern regions.

Goto Y., Ostermeyer Y., Ghazi Wakili K., Wallbaum H.: “Economic, ecological and thermo-hygric optimization of a vapor-open envelope for subtropical climate”. *Energy and Buildings* 55: 799-809, 2012.

5.1 Introduction

With regard to resource depletion and global climate change, there have been intensive discussions. Today it is widely recognized that the construction industry is playing a key role to envisage a rational use of resources and to realize a more sustainable society (CIB 1999). On a global scale, the construction industry contributes to about 30-40% of manmade greenhouse gas emissions and is responsible for about 50% of resource consumption (UNEP 2003). In order to improve the environmental performance of buildings, several design approaches for building envelopes and equipment have been proposed and implemented, mainly in cold/mild climate regions aiming for a high energy efficiency standard (for example (MINERGIE® Building Association) and (Passivhaus Institute)). However, it is becoming more and more important to take measures not only to reduce greenhouse gas emission, but also to enhance the fundamental environmental performance of the constructions. At the same time it is also important to take into account the regional conditions so that each technology is appropriately tailored and its targeted function is ensured and socially accepted.

The general concept of sustainability is often defined by the so-called triple bottom line model, which consists of ecological, economic and social pillars (Elkington 1998). Measures to be taken ideally enhance all these aspects of sustainability. However, it is often difficult to assess the impact of a building design and its realization on the environment and human society. For example, analyzing the impact of having thicker insulation is a very intricate process. Generally speaking in the construction industry, the thicker the insulation is, the less the energy consumption for heating is, the more expensive the construction is and the more resource-intensive the production phase will be. Defining the optimal construction, the applied materials and their dimensions is always a complex process because of the trade-offs between the three pillars of sustainability. Therefore an optimization method that deals with such trade-offs is needed to approach the overall life span of constructions from a holistic viewpoint.

In this study, the thickness of insulation for a vapor-open building envelope system, which was developed for subtropical regions, was investigated as a case study of such a design optimization model. Using both economic and ecological indicators, the optimal thicknesses of wood fiber insulation were quantified through this optimization model by taking into account the initial environmental load and cost as well as those in the use phase. The thermo-hygric minimum insulation thickness was also determined by hygrothermal models in order to ensure the longevity of the buildings. All these models were created with the conditions of Japan. The results were compared to each other and the applicability of this envelope system was discussed. It must be noted that social sustainability is disregarded in this study due to the complexity of properly quantifying it, even though this was thoroughly considered in the design philosophy of the envelope system. Also the service life of the insulation was considered separately from the service life of the building itself based on the assumption that the longevity of wood fiber is shorter than that of the structure of the building.

5.2 Methodology

5.2.1 Sustainable vapor-open envelope system for subtropical regions

The interest of energy consumption by buildings is growing in subtropical regions because of the high growth rate of urbanizing areas in these regions (CIB & UNEP-IETC 2002). The major difference between cold/mild regions and subtropical regions is the condition and the duration of summer. Due to hot and humid summer climatic conditions, energy for cooling and dehumidifying is consumed in order to create a comfortable indoor environment in addition to heating in the winter.

Besides the energy issue, summer conditions pose another point to be taken into account in the building design. From the viewpoint of building physics, such a climatic condition is very challenging because the direction of moisture flux due to the gradient of vapor pressure between exterior and interior changes throughout the year. In summer the moisture transfer happens from outside to inside and in winter vice versa. Inappropriate design of a building envelope, which fails to deal with the moisture flux, may result in interstitial condensation, the decay of building elements and mold growth in exterior walls. The mold growth would affect not only the longevity of the building but also the health of inhabitants (Jarvis et al. 2001). Directly implementing the conventional designing method for cold regions does not solve the fundamental problems in subtropical regions, hence, the introduction of a novel envelope system for subtropical regions is necessary.

Considering this issue, a new building envelope system was developed within the research team led by the authors. This envelope system mainly consists of major layers with natural materials, namely the external insulation layer with wood fiber board, the structural layer with cross laminated wooden panel and the interior finishing layer with a composite of wood and clay. The illustration of the envelope system and the materials for each layer is shown in Figure 5-1. The basic design philosophy of this system is that the envelope consists of hygroscopic materials with moderate vapor permeability. This system allows the moisture flux to move through the wall in both directions. By defining an appropriate thickness to each layer, it is possible to avoid moisture related problems inside the wall. The hygrothermal performance of the envelope has already been verified by full-scale wall experiments with climatic chambers and numerical simulations by a one-dimensional transient heat and moisture transfer model (Goto et al. 2011).

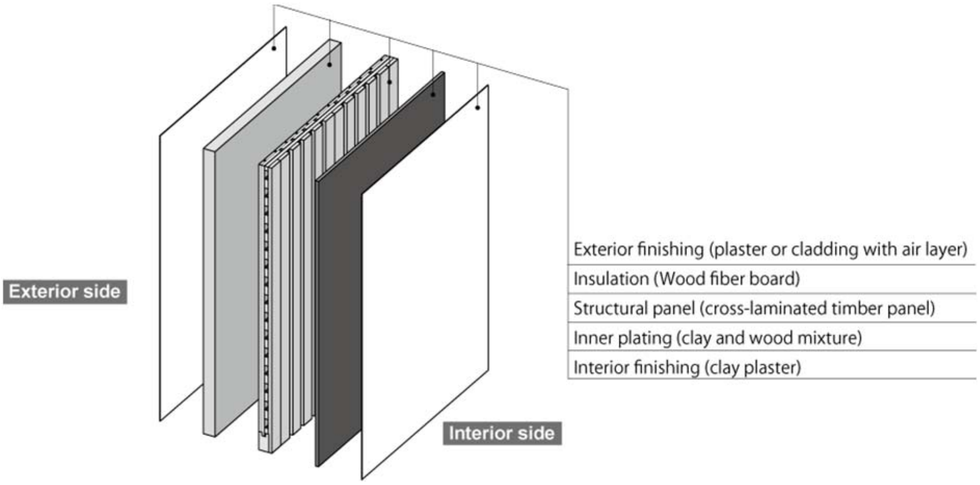


Figure 5-1: The layered structure of the envelope system

Besides the building physics considerations, the design philosophy of the envelope also comprises ecological, economic and social aspects. The components are based on renewable materials, so it may be produced using local resources, which contributes to less transportation being required for each component. Local production also promotes the local economy creating a local value chain. The local design conditions, namely local climatic conditions and socio-cultural aspect such as user behaviors (preferred room temperature/humidity, heating/cooling strategies and so on) can be taken into account in the envelope design.

Flexibility and adaptability to specific local conditions is assured by the layered structure of the envelope. This system enables the material of each layer and its thickness to be selected independently, for its primary function alone. Therefore the thickness of the insulation layer, which defines not only the thermal resistance but also the moisture sorption capacity, can be determined according to the local climatic condition without interrupting the other components such as the structural element. With this flexibility, an actual wall make-up can be determined considering the local conditions of both sides of the wall. In the present study this characteristic of flexible layer structure was applied to define the optimal insulation thickness.

5.2.2 Optimization of the insulation

5.2.2.1 Economic and ecological optimization

For economic and ecological analyses, the optimization method proposed by Boermans et al. (Boermans et al. 2008) was applied. In the model the initial and running costs, which are directly related to creating the insulation, are summed as the function of insulation thickness. The minimum value of the summed cost is given by the optimal insulation thickness. The model of the optimization is illustrated in Figure 5-2. This method was only applied to the economic optimization in (Boermans et al. 2008), but it is also applicable to the environmental optimization as long as the cost indicator is chosen and the cost itself is calculated correctly. It should be clarified that the ecological impact is expressed as "ecological cost" in the following according to this model.

The indicator for the economic analysis is economic cost. The price of heating/cooling energy and that of the installation of the insulation are summed up. As for the ecological optimum, the indicator to quantify the environmental load depends on the interest. A large number of internationally accepted environmental indicators exist (Althaus et al. 2010). In the present study Cumulative Energy Demand (CED) (VDI 1997), the CO_{2eq} factors from the Intergovernmental Panel on Climate Change (IPCC 2007 100a and IPCC 2007 500a) (Albritton et al. 2001), IMPACT 2002+ (Jolliet et al. 2003) and Ecological footprint (Huijbregts et al. 2007) were applied. The lifetime ecological cost resulting from the creation of the insulation and the cost resulting from the energy consumption for heating/cooling are summed as with the economic model.

It must be noted that the best practice is achieved by the optimal insulation thickness, but this is not necessarily a very strict point at which to aim. Both to the left and right of the optimal point, reasonably good solutions exist. In the present study, an optimal 10% range (the range which is defined by less than 110% of the optimal cost) was considered (see Figure 5-2). The economic and ecological optimal thickness range was then defined by the overlapping of each optimal 10% range.

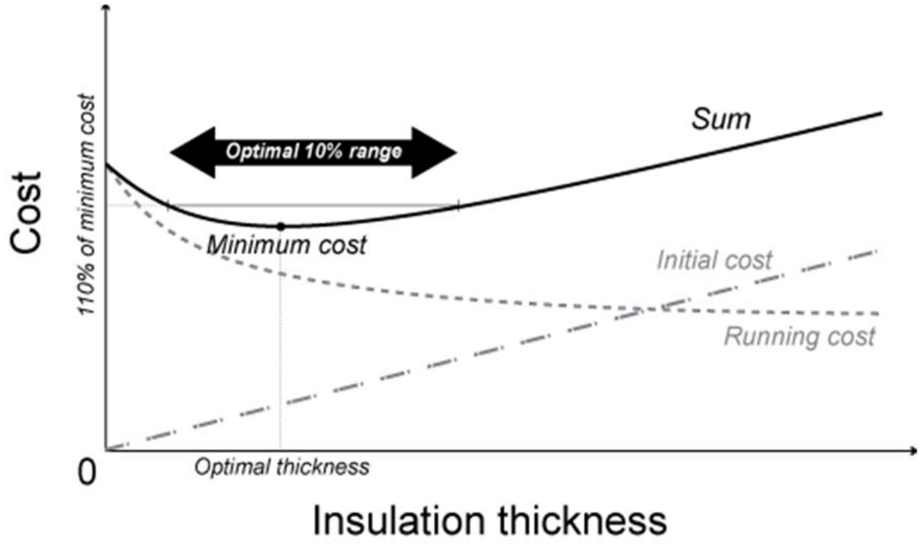


Figure 5-2: Insulation optimization model and the definition of optimal 10% range

5.2.2.2 Thermo-hygric optimization

A building physics analysis of a building has recently become more and more important in an effort to ensure a high level of indoor comfort, low energy consumption and no moisture-related risks in exterior walls (for example (Olalekan et al. 2006) and (Tariku et al. 2011)). In the present study the thermo-hygric assessment of the envelope system places its emphasis on the moisture related problems in the building envelope. This is because the primary concern of the envelope design philosophy was to make use of the hygroscopic properties of the components and reduce the moisture related risk as much as possible in order to ensure a longer building life span. The assessment was performed using a transient heat and moisture transfer model, which was introduced and validated in (Goto et al. 2011). The minimum thickness necessary to avoid a high relative humidity in the wall was defined using the statistical exterior climate data and the predicted room temperature and humidity based on a whole building heat and moisture balance model. The criterion of moisture accumulation was that the relative humidity never exceeds 80% in the wall element, which is difficult to replace for maintenance reasons, namely the structural element (cross laminated wood panel). Although this threshold for relative humidity (80%) was in fact rather low compared to the condition that mold growth is expected (Viitanen et al. 2010), this criterion allows a margin of safety.

5.2.3 Diverse climatic conditions of Japan

Japan has a wide range of climates due to its geographical characteristics. This climatic diversity should be carefully taken into account when discussing building designs. In the present study, Japan was divided into 5 zones in accordance with the Japanese law concerning the rational use of energy in the housing sector (Act on the rational use of Energy, Ministry of land, infrastructure, transport and tourism of Japan). Within this law the division of the zones was based mainly on the heating energy consumption, which reflects the regional climate diversity. This zoning is shown in Figure 5-3. Eight cities were chosen and used in the following models, namely Sapporo (zone 1), Morioka (zone 2), Sendai (zone 3), Tokyo (zone 4), Nagoya (zone 4), Hiroshima (zone 4), Fukuoka (zone 4) and Kagoshima (zone 5). Sapporo is actually in a continental climate region, but it was included in the following simulations to assess the diversity of the climate and the applicability of the envelope even in cold/mild regions as well. Four cities were selected from zone 4 (Tokyo, Nagoya, Hiroshima and Fukuoka) in order to investigate the regional difference within the same climatic zone covering a rather wide area. Table 5-1 shows each city’s monthly mean value of temperature and relative humidity between 1996 and 2005 according to METEONORM 6.1 (Meteotest).

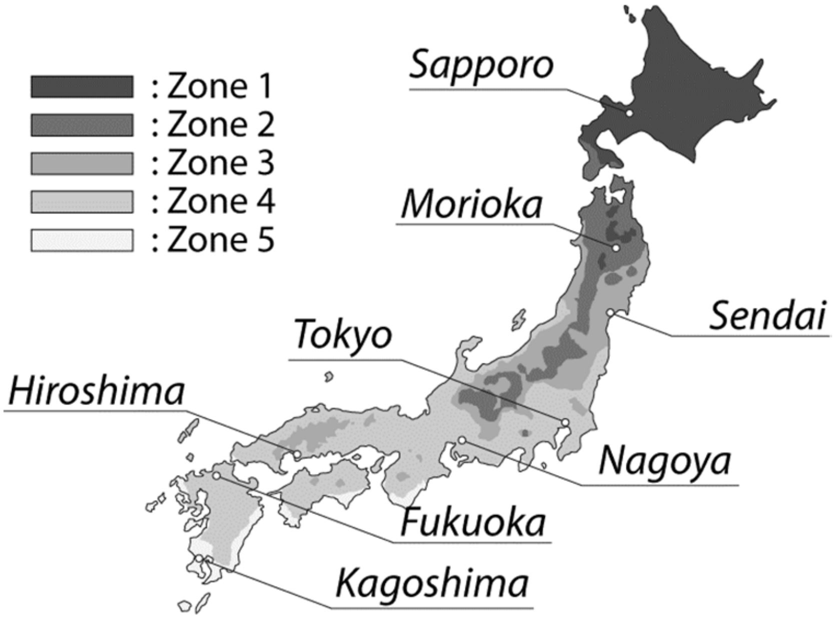


Figure 5-3: Climatic zones of Japan and the selected cities

Table 5-1: Monthly mean temperature (°C) and relative humidity (%) of the selected cities

	Jan.		Feb.		Mar.		Apr.		May		Jun.		Jul.		Aug.		Sep.		Oct.		Nov.		Dec.	
	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.	Temp.	R.H.
Sapporo	-3.6	69.4	-3.1	68.7	0.7	64.0	7.4	61.7	12.7	65.7	16.6	72.5	20.9	76.4	21.8	75.5	18.0	72.5	11.9	67.6	5.0	67.2	-2.1	88.0
Morioka	-1.9	74.1	-1.2	71.1	2.3	65.8	9.0	64.7	14.3	68.5	18.4	75.0	22.2	79.4	22.9	79.6	18.7	82.3	12.3	77.7	5.8	76.0	0.64	72.5
Sendai	1.7	67.1	2.1	64.6	5.4	59.1	10.8	62.3	15.2	70.1	18.7	78.5	22.7	81.4	23.7	81.0	20.5	80.4	15.4	72.2	9.3	68.7	4.2	66.2
Tokyo	6.3	49.6	6.8	49.3	9.8	55.0	15.1	62.4	19.2	70.1	22.4	75.3	26.5	74.7	27.2	74.7	23.7	75.0	18.7	68.3	13.4	62.1	8.6	51.8
Nagoya	4.5	65.5	5.3	61.5	8.9	57.9	14.7	60.0	19.4	66.4	22.7	74.2	26.9	72.6	27.9	70.0	23.9	73.7	18.2	69.1	12.3	68.3	6.9	67.1
Hiroshima	5.3	65.4	6.0	65.5	9.5	62.5	14.8	64.6	19.8	68.2	23.2	75.7	27.3	75.9	28.2	74.4	24.3	74.9	18.5	70.3	12.6	70.9	7.5	68.4
Fukuoka	6.6	62.9	7.5	61.4	10.8	61.4	15.5	64.3	20.0	66.7	23.3	73.9	27.2	73.7	28.2	71.5	24.4	73.7	19.4	66.9	13.9	67.0	9.0	62.7
Kagoshima	8.5	65.3	9.6	65.1	12.8	64.9	17.0	67.8	21.2	70.2	24.1	78.0	28.2	74.2	28.7	72.7	26.0	72.2	21.3	66.8	16.0	67.6	10.9	65.3

5.3 Economic and ecological optimization

5.3.1 Transmission heat loss model

A key factor in the economic and ecological performance of buildings is transmission heat loss because the regulation of indoor climate is closely related to the consumption of energy and resources. Transmission heat loss is mainly caused by poor insulation and air infiltration, which are results of inappropriate design or poor craftsmanship. A number of sophisticated transmission loss models of buildings exist (Woloszyn et al. 2008). However, regarding the economic and ecological optimization of insulation, only simple models have been used within European conditions ((Boermans et al. 2008), (Ostermeyer et al. 2011) and (Dylewski et al. 2011)). Jaber et al. conducted an economic optimization analysis of the insulation of a residential building under Mediterranean climatic conditions of Jordan using a sophisticated transmission heat loss model by TRNSYS (TRNSYS 2006), but the moisture interaction between the building envelope and the ambient air and ecological optimization was disregarded (Jaber et al. 2011). The simple models (((Boermans et al. 2008), (Ostermeyer et al. 2011) and (Dylewski et al. 2011)) were based on the heat transmission coefficient U. Even though there are slight differences among the models, the principle of the models can be described by equation (5-1),

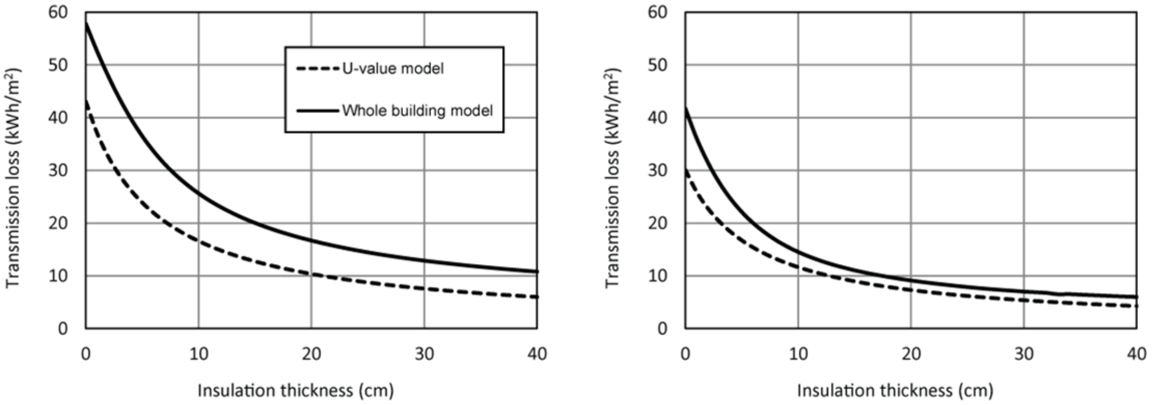
$$Q_{U-value} = {}^{24}\!\!\diagup\!_{1000} \cdot D \cdot U \tag{5-1}$$

where $Q_{U\text{-}value}$ (kWh/m^2) is transmission heat loss of a unit area of the building envelope based on a U-value model, D (K•day) is the sum of heating and cooling degree days of the given place, and U (W/m^{2}K) is the heat transmission coefficient of the given envelope. This model is rather simple especially when comparing the energy performance of buildings under different building physics conditions, such as exterior humidity, solar gain, the setting of building equipment and preferred room temperature and humidity.

The authors have introduced the whole building heat and moisture balance model based on the envelope system (Goto et al. 2012). Within this method, the transmission heat loss is calculated in accordance with the international standard ISO 13790 (ISO 13790 2007) considering the user behavior on preferred temperature, opening of windows, closing of shading devices and so on. Furthermore, the interaction of moisture between the exterior and interior air via the envelope and building equipment (ventilation system) is considered, including moisture buffering by interior finish materials. By conducting the complete package of the whole building simulation, the transmission heat loss, indoor temperature and relative humidity can be acquired.

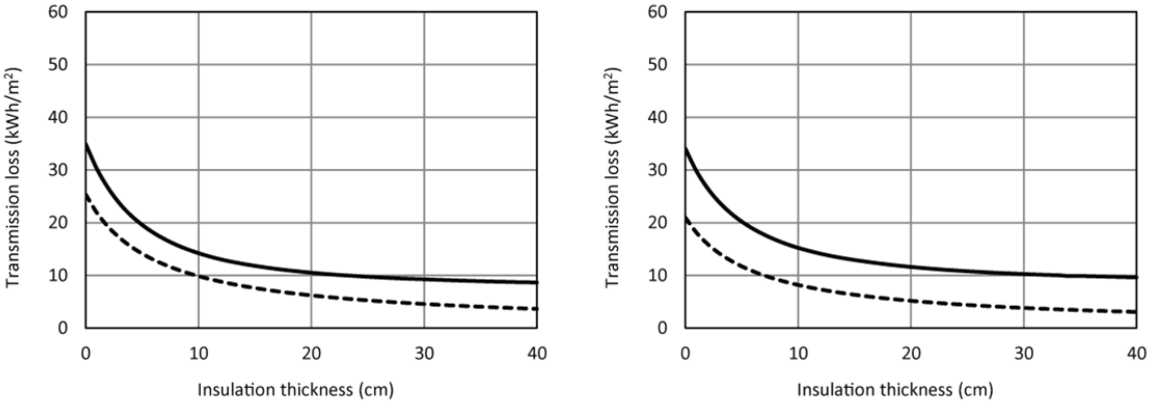
In order to gain the actual transmission heat loss value, it is necessary to include the building design. The above mentioned calculation was applied to the building described in (Goto et al. 2012). The set point temperature for heating and cooling was at 20°C and 27°C respectively. Other details of the building settings are given in (Goto et al. 2012). Important boundary condition set in (Goto et al. 2012) is also applied in the present study.

Figure 5-4 shows the comparison of the calculated transmission heat loss between the U-value model and the whole building model on Sapporo, Sendai, Nagoya and Fukuoka when applying the same set point temperature. The difference between the U-value model and the whole building model was observed to be 20-70%. The other four cities (Morioka, Tokyo, Hiroshima and Kagoshima) also showed the same tendency of the difference. The degree of difference itself also differed according to the local conditions, comparing the case of Sendai (Figure 5-4(b)) and others. Therefore the whole building transmission heat loss model using the local condition of each city was used in the following optimization models.



(a) Sapporo

(b) Sendai



(c) Nagoya

(d) Fukuoka

Figure 5-4: Comparison of transmission loss, U-value model vs. whole building model

5.3.2 Economic optimization

5.3.2.1 Ecological optimization model

The economically optimal point is given by the minimum value of equation (5-2),

$$C_{total} = C_{initial} + C_{running} \tag{5-2}$$

where C_{total} (JPY/m^2) (JPY expresses Japanese yen) is the sum of the economic costs, $C_{initial}$ (JPY/m^2) is the cost of creating a unit area of the insulation, and C_{runnig} (JPY/m^2) is the cost due to transmission loss per unit area of the envelope. It should be noted that the difference of the currency does not change the model's meaning. Japanese yen can be replaced by any other currencies. The cost for maintenance of the insulation is disregarded in the present model. The cost for creation and disposing of the insulation layer is also disregarded because it is intricate to separate those costs from the total construction cost based on the conventional methods.

The initial investment $C_{initial}$ is given by equation (5-3),

$$C_{initial} = P \cdot d \tag{5-3}$$

where P (JPY/m^3) is the cost of the insulation material per volume and d (m) is the thickness of the insulation. In this model the non-linear change of the cost is disregarded. Non-linear cost change occurs, for example, when the insulation layer becomes thicker that the insulation needs to be supported or connected with elements different than conventional ways.

The running cost over the service life of the building C_{runnig} is given by equation (5-4),

$$C_{running} = n \cdot E_{money} \cdot Q \tag{5-4}$$

where n (years) is the service life of the insulation, E_{money} (JPY/kWh) is the energy price per 1 kWh and Q (kWh/m^{2}a) is the yearly transmission loss per unit area of the envelope.

5.3.2.2 Input for the economic optimization model

The material cost P was set at 28 000 JPY/m^3 according to the prices set by the distributor of the material. The service life of the insulation was assumed to be 30 years. The heating and cooling energy was assumed to be supplied only by electricity. The price of energy provided by electricity was given at 21.6JPY/kWh (Jyukankyo Research Institute Inc. 2005). The climatic data of each city was generated with METEONORM 6.1.

5.3.2.3 Result of the economic optimization

Figure 5-5 shows the curve of $C_{initial}$ and C_{runnig} of the analysis for Nagoya as an example. *(The individual result for each of the investigated cities is presented in Appendix C, Figure C-1.)* Figure 5-6 shows the economically optimal 10% range of the insulation thickness (see Figure 5-2) of the 8 investigated cities. Table 5-2 lists the economic optimal insulation thickness of each city. The optimal insulation thickness became thicker for those cities situated in a colder region. Considering that the energy consumption was only calculated for heating and cooling (dehumidification was performed only by passive measures, see (Goto et al. 2012)) and the transmission heat loss increased as the city is located further north (see Figure 5-4), this indicates that the most dominant factor for defining the economic optimum was the heating demand.

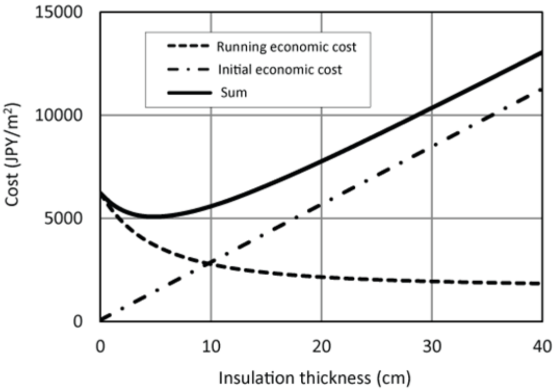


Figure 5-5: Economic analysis for Nagoya

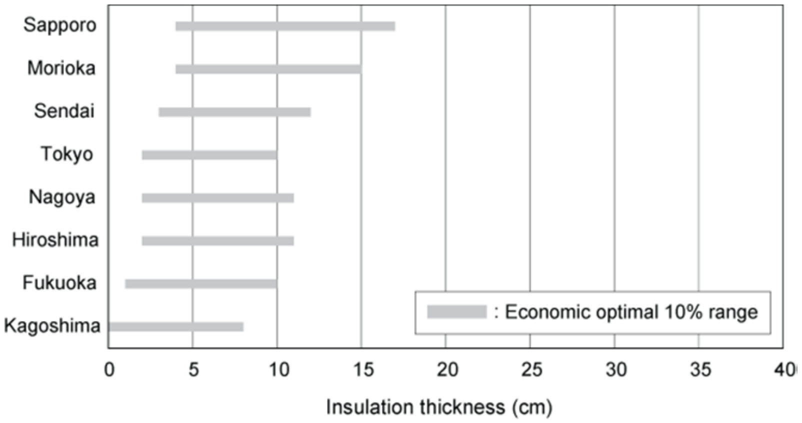


Figure 5-6: Economic optimal 10% range for the 8 investigated cities

Table 5-2: Economic and ecological optimal insulation thickness of 8 cities

	Economic optimal thickness (cm)	Ecological optimal thickness (cm)					Thermo-hygric minimum thickness (cm)
		CED	IPCC100	IPCC 500	Impact 2002+	Ecological footprint	
Sapporo	9	20	28	29	26	31	2
Morioka	8	18	26	27	24	29	4
Sendai	7	15	20	20	19	22	6
Tokyo	4	11	16	16	15	18	2
Nagoya	5	12	17	17	16	18	4
Hiroshima	5	12	18	18	16	19	6
Fukuoka	4	12	17	17	15	19	5
Kagoshima	3	10	13	13	12	15	6

5.3.3 Ecological optimization

5.3.3.1 Ecological optimization model

The ecologically optimal point is given by the minimum value of equation (5-5),

$$I_{total} = I_{initial} + I_{running} \tag{5-5}$$

where I_{total} (Pt/m^2) is the sum of the ecological costs, $I_{initial}$ (Pt/m^2) is the environmental cost of creating a unit area of the envelope and $I_{running}$ (Pt/m^2) is the environmental cost due to transmission loss per unit area of the envelope. The ecological cost due to maintenance and dismantling of the insulation is disregarded in the present model. As a wide range of indicators can be applied to this general model, the unit is expressed in Pt (point) so that an individual unit definition of each indicator would apply.

The initial effort $I_{initial}$ is given by equation (5-6),

$$I_{initial} = K \cdot d \tag{5-6}$$

where K (Pt/m^3) is a coefficient for environmental load due to creating the insulation material per volume, with the unit differing from one indicator to another. The factor of environmental impact due to the transportation of the material and the construction work were disregarded.

The running cost over the service life of the insulation $I_{running}$ is given by equation (5-7),

$$I_{running} = n \cdot E_{envi} \cdot Q \tag{5-7}$$

where E_{envi} (Pt/kWh) is a coefficient for environmental load due to producing the energy of 1 kWh.

5.3.3.2 Input for the ecological optimization model

The coefficient for environmental load due to material production K was determined by applying the existing database EcoInvent V2.2 (SCLCI 2011). As with the economic analysis, the detailed inputs for each indicator are listed in Table 5-3. The heating and cooling energy was assumed to be supplied only by electricity. The point for environmental load due to electricity production E_{envi} was determined by the commercial program SimaPro (PRé Consultants) applying the energy mix of primary energy production of Japan in 2010 (nuclear: 38%, coal: 28%, natural gas: 24%, solar: 1%, water and others: 9%) (Takahashi et al. 2011). The detailed inputs for each indicator are listed in Table 5-3.

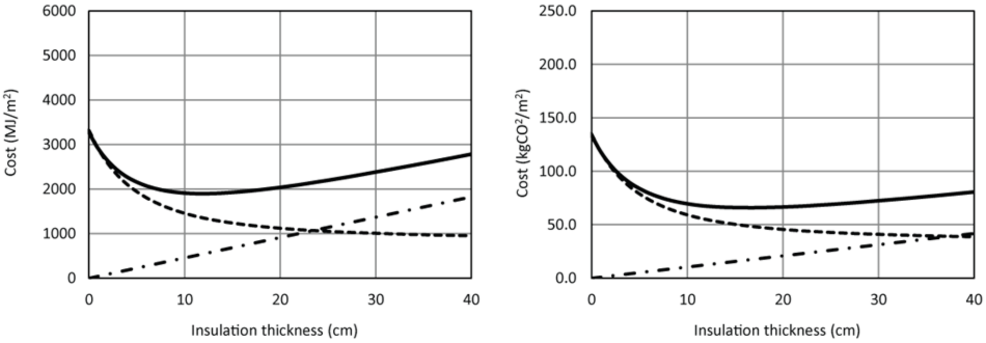
Table 5-3: Coefficient for environmental load due to material production K and electricity production E_{envi} and E_{envi}^* (energy mix 2030)

	K (Pt/m^3)	E_{envi} (Pt/kWh)	E_{envi}^* (Pt/kWh)
CED (Pt=MJ)	4 566	11.6	11.3
IPCC100 (Pt=kgCO$_2$)	104.5	0.47	0.62
IPCC500 (Pt=kgCO$_2$)	100.3	0.46	0.60
Impact 2002+ (Pt=Pt)	0.0393	1.58E-04	1.69E-04
Ecological footprint (Pt=Pt)	409.7	2.20	1.98

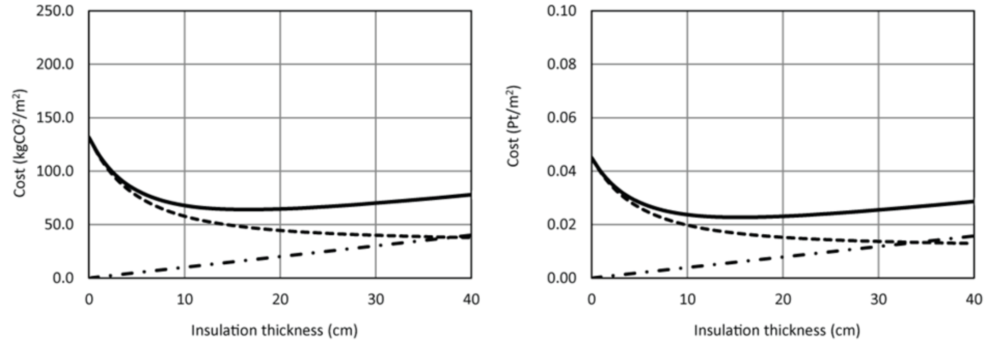
5.3.3.3 Result of the ecological optimization

Figure 5-7 shows the curves of $I_{initial}$ and I_{runnig} of the analysis of Nagoya as an example. *(The individual result for each of the investigated cities is presented in Appendix C, Figure C-2 – C-9.)* Figure 5-8 shows the ecologically optimal 10% range of the insulation thickness of each 8 cities defined by the overlapping of all the indicators. Table 5-2 lists the optimal insulation thickness for each indicator of each city.

The optimal insulation thickness became thicker for those cities situated in a colder region. This indicates that the most dominant factor to define the ecological optimum was the heating demand as with the economic analysis.



(a) CED (b) IPCC 100



(c) IPCC 500 (d) Impact 2002+

Figure 5-7: Ecological analysis for Nagoya

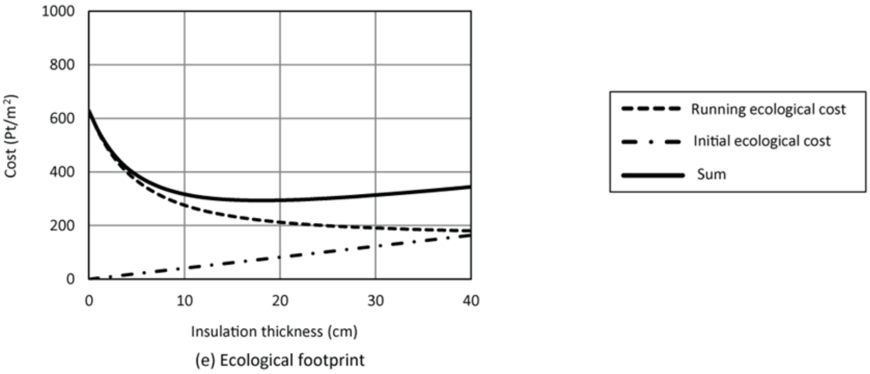


Figure 5-7 (cont.): Ecological analysis for Nagoya

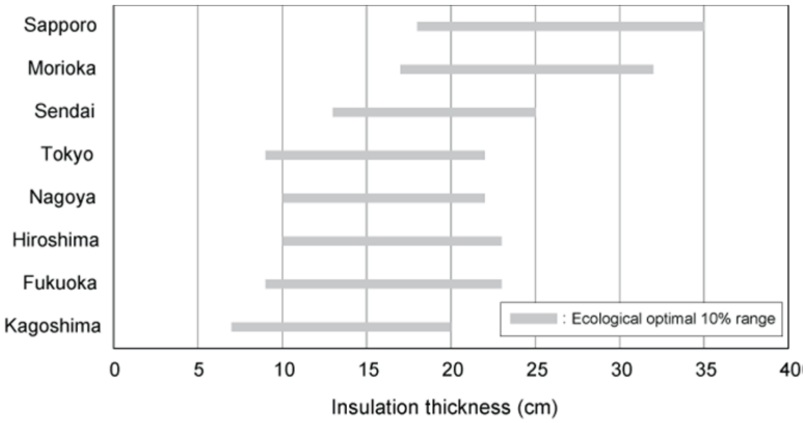


Figure 5-8: Ecological optimal 10% range for the 8 investigated cities

5.4 Thermo-hygric optimization

5.4.1 Heat and moisture transfer simulation

The heat and moisture transfer across the building envelope system was investigated under the climatic conditions of the above mentioned cities. WUFI Pro 4.2® (Fraunhofer Institute for Building Physics) was employed to carry out the one-dimensional transient heat and moisture transfer simulations. Within this program, the basic heat and mass transfer is modeled by equation (5-9) and (5-10). Those are solved simultaneously and the temperature and relative humidity across building component assembly is calculated (Künzel 1995),

$$\frac{dH}{d\theta}\cdot\frac{\partial\theta}{\partial t}=\nabla\cdot\left(\lambda\nabla\theta\right)+h_v\nabla\cdot\left(\delta_p\nabla\left(\varphi p_{sat}\right)\right) \tag{5-9}$$

$$\frac{dw}{d\varphi}\cdot\frac{\partial\varphi}{\partial t}=\nabla\cdot\left(D_\varphi\nabla\varphi+\delta_p\nabla\left(\varphi p_{sat}\right)\right) \tag{5-10}$$

where $dH/d\theta$ (J/m^{3}K) is the heat storage capacity of the material, $dw/d\varphi$ (kg/m^3) is the moisture storage capacity of the building material, λ (W/mK) is its thermal conductivity, D_φ (kg/ms) is its liquid transport coefficient, δ_p (kg/msPa) is its water vapor permeability, h_v (J/kg) is evaporation enthalpy of water, p_{sat} (Pa) is the water vapor saturation pressure, θ (°C) is the temperature and φ (-) is the relative humidity. The calculation of WUFI Pro 4.2® deals with the heat and mass transfer balance simulation as one dimensional phenomenon.

Regarding the exterior climatic boundary conditions, the expanded AMeDAS data in the format for WUFI simulation was applied (Fraunhofer Institute for Building Physics). It contains the hourly data of temperature, relative humidity, solar radiation and precipitation. As for the indoor climate, the predicted indoor temperature and relative humidity by the whole building heat and moisture balance simulation was applied (See 5.3.2).

The façade of the building was assumed to have wooden cladding with ambient air going through the air layer, which is a common façade solution in Japan. Therefore the influence of solar radiation and rain was neglected in the calculation. The heat resistance of the exterior wall (under the air layer) was set at 0.0588m^2 K/W, which is a conventional value. S_d-value (equivalent air layer thickness in terms of vapor transfer) on the exterior surface was set at 0m, which meant there was no vapor retarding finishing on the surface of wood fiber insulation. The heat resistance of the interior surface was set at 0.125m^2 K/W, which is also a conventional value. S_d-value was set at 0.057m. This is the S_d-value of the plaster, which was assumed to be applied as the interior finish. In order to achieve more reliable simulations, the input of material properties was based on the measurement, taking into account variability due to differences in moisture condition [8]. The initial condition was set at 10°C and 40%RH. The calculation period was set at three years so that the influence of the initial condition becomes negligible.

5.4.2 Result of thermo-hygric optimization

The predicted relative humidity of a model (the insulation of 40mm under the condition of Nagoya) is shown in Figure 5-9. The monitoring position of this is the point that reached the highest relative humidity in the structure panel. It was observed that the minimum insulation thickness to avoid a moisture problem is highly dependent on the local climatic conditions. In Table 5-2, the minimum thickness of the insulation to avoid moisture accumulation under the climatic conditions of the 8 investigated cities is shown.

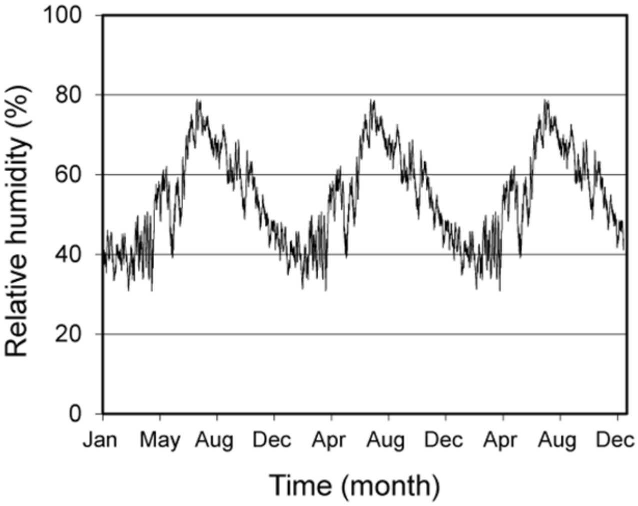


Figure 5-9: Predicted relative humidity (insulation of 40mm under the condition of Nagoya)

5.5 Discussions

5.5.1 Comparison between economic, ecological and thermo-hygric analyses

As described above, the economic, ecological and thermo-hygric optimization analyses were conducted using the vapor-open envelope system. The summary of those analyses is shown in Figure 5-10. The bands represent the economic and ecological optimal 10% ranges and their overlapping. The star (☆) represents the minimum insulation thickness which was given by the thermo-hygric analyses.

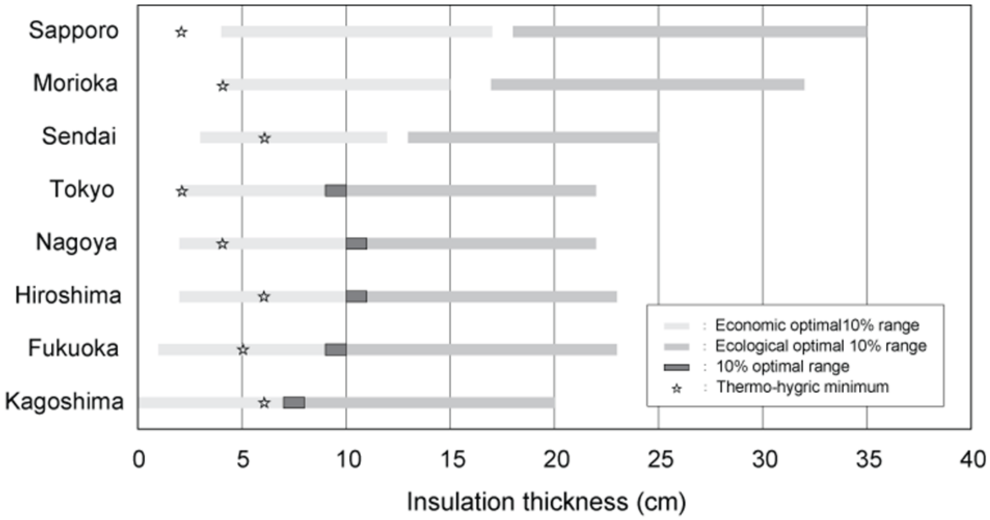


Figure 5-10: Summary of economic, ecological and thermo-hygric optimization

The ecological optimal thickness was larger than the economic optimal thickness in all cases. The overlapping of the economic and ecological optimal 10% ranges was observed in the cases of the central and southern cities (Tokyo, Nagoya, Hiroshima, Fukuoka and Kagoshima). The overlap of economic and ecological optimal insulation ranges was larger than the thermo-hygric minimum thickness in those cases. In the case of northern cities (Sapporo, Morioka and Sendai), the economic and ecological optimal 10% ranges did not overlap. The main reason for this is the relatively high price of the insulation material. From the viewpoint of consumers (the viewpoint of how much a consumer needs to pay for having insulation over its service life and eventual heating and cooling load), it is very likely that the decision of insulation thickness is made purely by the economic incentive. In order to minimize the environmental load, it is recommended that the gap between the economic and ecological optimal range would be filled by governmental policies such as subsidizing the additional insulation, implementing obligatory regulation on transmission loss or setting the electricity price higher.

Except for the case of Sapporo, the thermo-hygric minimum thickness was within the economic optimal 10% range. This indicates that the decision purely derived from the economic optimization might result in an insufficient amount of insulation to ensure the longevity of the building. In the case of Sapporo, the thermo-hygric minimum thickness was even smaller than the economic optimal 10% range. This implies that the moisture sorption capacity of the envelope is not highly required in this region. The wood fiber insulation may be replaced with another material, which has less sorption capacity as long as the alternative has the same or less environmental load within the same functional unit (the same level of thermal resistance).

5.5.2 Sensibility study on the future situations

The model discussed above assumes that the current economic situation will stay the same over the service life of the insulation. However, this is not obviously the case. There has been the tendency of the increasing and the strongly fluctuating oil/gas price since January 2004. The Japanese economy is also facing transition due to population decline (Keidanren the 21st Century Public Policy Institute 2012). Furthermore, the future of Japanese electricity production is still very unclear after the nuclear plant accident in 2011. Those aspects should be taken into account when conducting the assessment of systems that have a rather long lifetime. In this section, the interest rate of the Japanese currency, the increase of electricity price and the change of the mix of primary energy are dealt with in order to further investigate the feasibility of the proposed envelope system.

The interest of the currency and the energy price increase were taken into account by the discount cash flow method. The discount rate S_n is given by equation (5-11) and the adjusted cost $C_{total,Sn(s,r)}$ and $I_{total,Sn(s,r)}$ are given by equation (5-12) and (5-13) respectively,

$$S_{n(s,r)} = \sum_{t=1}^{n} \left(\frac{1 + {}^{s}\!/_{100}}{1 + {}^{r}\!/_{100}} \right)^{t} \tag{5-11}$$

$$C_{total,Sn(s,r)} = C_{initial} + S_{n(s,r)} \cdot E_{money} \cdot Q \tag{5-12}$$

$$I_{total,Sn(s,r)} = I_{initial} + n \cdot E_{envi} \cdot Q \tag{5-13}$$

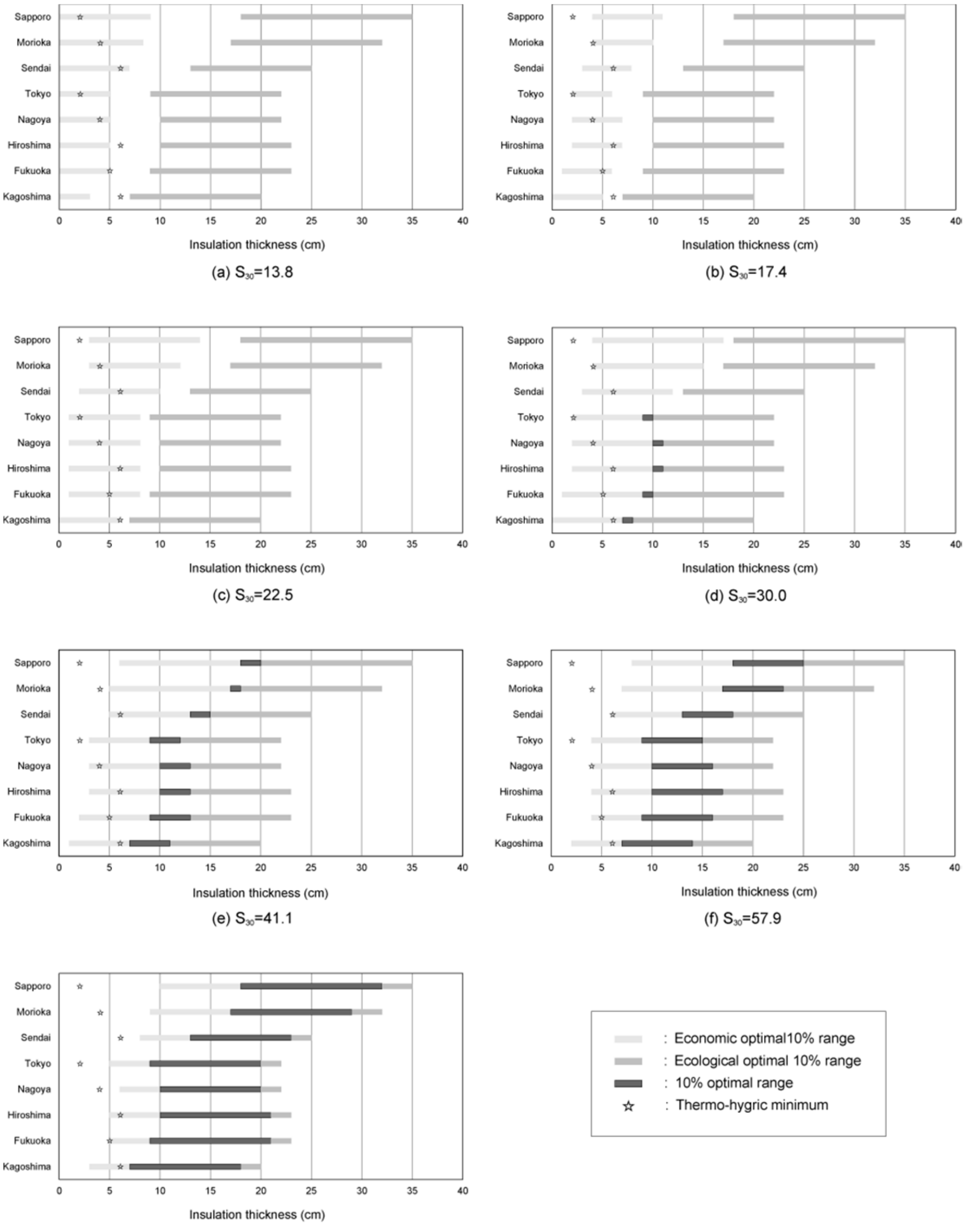
where n (years) is the service life of the insulation, s (%) is the energy price increase rate and r (%) is the interest rate. Equation (5-13) is basically the same as equation (5-5). It should be noted that the environmental impact is independent from the economic situation. In the following, the service life was defined as 30 years (n=30) in accordance with the original model. Since the future economic situation is unclear, rates of 0, 2, 4 and 6% were applied to each r and s. Table 5-4 lists the calculated S_{30} with all the combinations of s and r. Seven scenarios of S_{30} was identified from this table, namely S_{30}=13.8, 17.4, 22.5, 30, 41.1, 57.9 or 83.8.

Table 5-4: S_{30} scenarios with the combinations of interest rate s and electricity price increase r

		Interest rate r (%)			
		0	2	4	6
Price increase s (%)	0	30.0	22.4	17.3	13.8
	2	41.4	30.0	22.5	17.5
	4	58.3	41.1	30.0	22.6
	6	83.8	57.5	40.9	30.0

The energy mix scenario of an eventual decommissioning of nuclear plants was also considered in addition to the current energy mix. This energy mix prediction for 2030 (hereafter called “energy mix 2030”) was cited from (Takahashi et al. 2011) (nuclear: 14%, coal: 25%, natural gas: 50%, solar: 2%, water and others: 9%). In the prediction model, it was assumed that (1) there will be no more new nuclear plants constructed and (2) there will be no extensions of the life span of the existing nuclear plants. The point of ecological load E_{envi} was recalculated using SimaPro according to this energy mix scenario. The adjusted coefficient E_{envi}^* is listed in Table 5-3. *(The individual calculation result for each indicator and for each city is presented in Appendix C, Figure C-10.)*

The results of optimization summary with the 7 S_{30} scenarios are given in Figure 5-11. The comparison of the current energy mix and energy mix 2030 in the case of (n, s, r) = (30, 4, 2) (i.e. S_{30} = 41.1) is presented in Figure 5-12. *(The rest of the results for energy mix 2030 are presented in Appendix C, Figure C-11.)* The difference of the interest rate S_{30} resulted in a significant difference of the overlapping ranges. The difference of the energy mix resulted in a rather minor difference. It was shown that the most dominant factor is the discount rate, namely the future economic situation. Taking into account the rather low interest rate of Japan (Bank of Japan) and the low GDP growth prediction of Japan (Keidanren the 21st Century Public Policy Institute 2012), which is supposed to have correlation with the electricity price (Soytas et al. 2003), a realistic discount rate S_{30} is assumed to be given by (s, r) = (0-2, 2-4), namely S_{30} = 30, 41.1 and 57.9 in the presented scenarios. Hence it can be said that the construction of buildings with the given envelope system is feasible in Japan, especially in the central and southern regions, from economic, ecological and thermo-hygric viewpoints.



(a) S_{30}=13.8

(b) S_{30}=17.4

(c) S_{30}=22.5

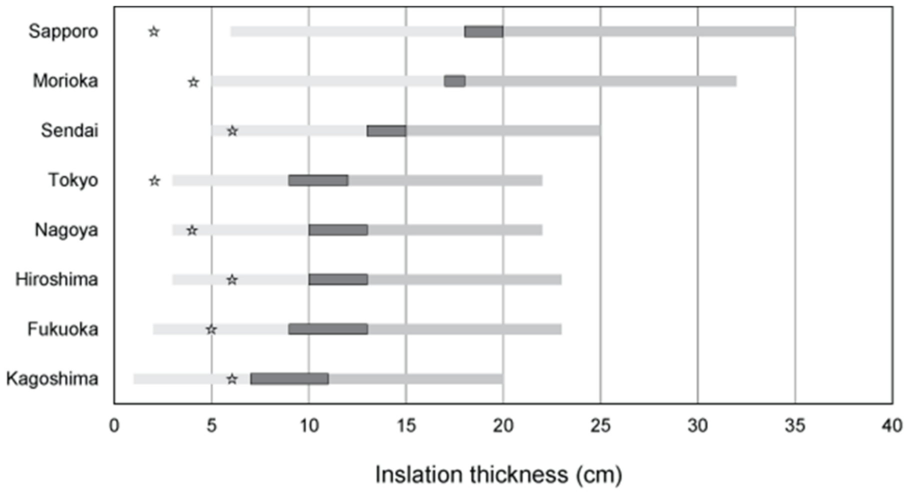
(d) S_{30}=30.0

(e) S_{30}=41.1

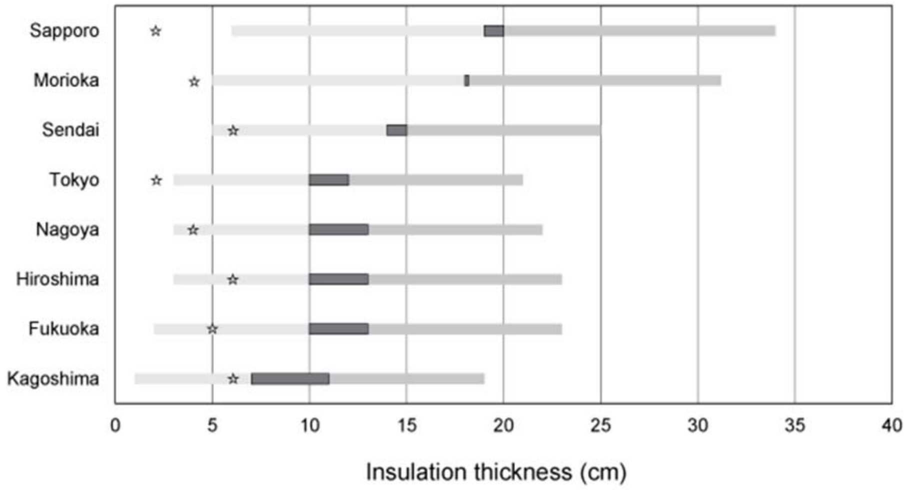
(f) S_{30}=57.9

(g) S_{30}=83.8

Figure 5-11: Optimal 10% range of the 8 cities with 7 S_{30} scenarios



(a) Current energy mix



(b) Energy mix 2030

Figure 5-12: Comparison of energy mix scenarios when S_{30}=41.1

5.6 Conclusion

In the present study a vapor-open envelope system for subtropical climates and a method to optimize its insulation thickness was introduced. The analyses were conducted using economic, ecological and thermo-hygric models for 8 cities, which represent the wide range of Japanese climatic conditions. The following findings were made;

1. The sophisticated transmission heat loss model contributed to a more reliable optimization model, better reflecting the variability of local climatic conditions than conventional methods.
2. The ecological optimal thickness was greater than the economic optimal thickness in all cases.
3. The thermo-hygric minimum thickness is dependent on local climatic conditions and was within the economic optimal 10% range except for the case of Sapporo. The decision of insulation thickness driven only from an economic perspective may result in moisture related problems in buildings.
4. In the northern region, the thermo-hygric minimum thickness was even smaller than the economic optimal thickness range. Therefore the insulation material could be replaced with an alternative with less moisture sorption capacity as long as it has the same or less environmental impact while providing the same thermal performance.
5. The interest rate and increase of the cost of electricity have a significant influence on the result of the optimization analysis.
6. The differences of energy mix 2030 result in a minor difference in the optimization model.
7. By conducting the economic, ecological and thermo-hygric analyses with consideration of future economic situations, it was shown that the application of the envelope system is feasible in Japan, especially in the central and southern regions.

In order to enhance the reliability and the applicability of the model, the following improvements would be beneficial.

- Regional conditions other than the climate should be taken into account. In reality there are regional differences in the costs of energy and material. The energy mix should also reflect local conditions.
- The heating and cooling energy in the model should include alternative strategies run by other energy carriers, such as oil, wood pellet and so on.

- The costs of the creation and the disposal of the insulation as well as the non-linear effect of cost increase for creating the insulation should be considered.
- The service life of the insulation should be further investigated based on more elaborated material longevity, taking into account the cost of maintenance and disposal as well.
- In addition to Japanese conditions, this model should be applied to the conditions of other subtropical regions as well.
- The concept of the overall optimization method may be applied to other construction systems.

5.7 Acknowledgement

The authors express their gratitude to the innovation promotion agency Commission for Technology and Innovation of the Swiss Confederation for the financial support for the overall framework of the project (grant 9755.1 PFIW-IW). Prof. Dr. Ralph Eichler (ETH Zurich) is greatly acknowledged for his financial support to accomplish the research. Edwin Zea (ETH Zurich) is also acknowledged for his contribution to the ecological model.

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6 Conclusion

6.1 Conclusion

With regard to climate change mitigation, the precondition formulated for this thesis was that emerging technologies should ensure a low environmental impact by its design, be affordable and be adaptable to local conditions.

Among many global issues, resource depletion and the rapid urbanization of developing regions are key issues. As a material resource, wood has become a very important renewable resource due to its nature of absorbing and storing CO_2. Also, because many emerging regions and considerable areas of developed regions are located in a subtropical climate, technology development which takes usage in a subtropical climate into account is key in order to contribute to the creation of a more sustainable society.

It is widely recognized that the construction industry plays a key role concerning resource depletion and the rapid urbanization of developing regions. As IEA (IEA 2011) formulated, measures for enhancing the efficiency of buildings and the scaled-up deployment of energy efficient buildings are as follows:

- mandatory building energy codes and minimum energy performance that aim to minimize life-cycle cost should be implemented,
- the development and deployment of buildings with net-zero energy consumption,
- the energy efficiency of existing buildings needs to be improved,
- the use of building energy labels or certificates should be promoted in order to provide information to owners, buyers and renters,
- the energy performance of building equipment should be improved.

The Japanese construction industry has great potential for making improvements with the issues described above. Also, considering the characteristics of its own industry and subtropical climate, a vapor-open wood-based envelope system was developed.

In this thesis, the hygrothermal performance of the envelope, the energetic performance of a building with the envelope system and economic and ecological optimal insulation thickness of the building were investigated in order to evaluate the feasibility of deploying the envelope system in Japan.

In order to investigate the durability of the envelope system, the thermal and hygric responses of two types of full-scale wall specimens were investigated by climate chamber tests and transient heat and moisture transfer simulations. Subsequently, the prediction of relative humidity inside the wall under the climatic condition of Kyoto was also attempted to evaluate the risk of moisture accumulation.

The following findings were made:

1. Both measured and calculated results corresponded to each other with sufficient accuracy.
2. The simulation using the real climatic data of Kyoto showed that the highest relative humidity between the insulation layer and structural panel was below 80 %RH throughout the simulation period of 3 years.

It was accordingly concluded as follows:

1. The hygrothermal model employed is appropriate for simulating the thermal and hygric response of the envelope system.
2. The envelope system ensures the absence of moisture related problems under the Japanese subtropical climate with the given insulation thickness of 80 mm.

In order to investigate the energetic performance of a building with the envelope system, a heat and moisture balance simulation of a building with the envelope system was proposed. In addition to the hygrothermal model of the envelope, a heat balance simulation in accordance with ISO 13790 and a moisture balance model, taking into account the dynamic moisture buffering by the interior materials, was integrated into the whole structure of the simulation model.

The prediction of the Moisture Buffer Value (MBV) of the interior finish materials of the envelope system was attempted using the transient heat and moisture transfer model. Subsequently the model was validated by the actual moisture buffering tests of those materials. Finally the whole building simulation was carried out using a model plan of a house (Test House, see Appendix A) using the climatic condition of Hikone.

Following findings were made:

1. The MBVs of the clay board, the plastered clay board and the plastered wood fiber/clay composite board were predicted with high accuracy. However, that of pure wood fiber/clay composite board was 42% higher than the experimental value.
2. It was indicated that the moisture buffering property of wood and wood-based materials might be modeled with the Fickian model, in which modified vapor diffusion resistance is applied.

3. The thickness of the plaster used in the study (8 mm) was thicker than the penetration depth of the plaster’s moisture buffering property.
4. The heating and cooling energy demand of the model house was 9.4 kWh/m^{2}a and 14.5 kWh/m^{2}a respectively. No energy consumption for dehumidification was accounted because of the radiator-based dehumidification strategy.
5. The moisture buffering significantly contributed to the reduction of the relative humidity fluctuation of the indoor air. This also resulted in a more stable air acceptability index.

It was accordingly concluded as follows:

1. It is suggested that experimental MBV shall be used for moisture balance simulations when modeling the moisture buffering of woods and wood-based materials, unless models that can take the nonlinear moisture conductance into account are available.
2. More holistic studies of the relationship between of the experimental MBV and the vapor diffusion resistance factor of woods and wood-based materials might give a standardized method to predict MBV of those materials.
3. When designing the interior finishing and enhancing its moisture buffering performance, the system within the penetration depth should be carefully designed.
4. The utilization of the building envelope system has a high potential low-energy-consuming and durable houses in subtropical regions.

In order to investigate the feasibility of applying the envelope system to Japanese conditions, the model to define the economic and ecological optimal insulation thickness of the model building was created using the whole building heat and moisture balance model, simplified Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) method. A thermo-hygric minimum insulation thickness that would ensure the longevity of the envelope was also determined. The optimization model was applied to the model building (Test House) under the climatic conditions of 8 Japanese cities (Sapporo, Morioka, Sendai, Tokyo, Nagoya, Hiroshima, Fukuoka and Kagoshima (listed from north to south)), also considering several economic and environmental future scenarios.

Following findings were made:

1. Compared to the simplified heat transmission loss model used in conventional LCCA methods, the sophisticated one used in this study contributed to a more reliable optimization model, reflecting the variability of local climatic conditions.

2. The ecological optimal thickness was larger than the economic optimal thickness in all cases.
3. The thermo-hygric minimum thickness was dependent on the local climatic conditions and it was within the economic optimal 10% range except for the case of Sapporo.
4. The interest rate and the electricity price have a significant influence on the result of the optimization analysis.
5. The difference of energy mix scenarios considering the nuclear power policy of Japan resulted in minor difference in the optimization analysis.

It was accordingly concluded as follows:

1. In order to minimize the environmental load, the gap between the economic and ecological optimal range should be filled by governmental policies, such as subsidizing the additional insulation, implementing obligatory regulation on transmission heat loss or setting the electricity price higher.
2. Since the thermo-hygric minimum thickness was smaller than the economic optimal range in the northern city (Sapporo), the insulation material could be replaced by an alternative with less moisture sorption capacity as long as it has the same or less environmental impact while providing the same thermal performance.
3. The envelope system is feasible for application in Japan, especially in the central and southern regions when considered from economic, ecological and thermo-hygric viewpoints.

6.2 Discussions and outlook

Other than the findings and conclusions addressed above, there are specific issues under Japanese conditions which should be further discussed.

Comparing the energy efficiency of the model building (Test House) and the Japanese energy standard (Next-generation Energy Standard (see 1.2.1.4)), the sum of the heating and cooking loads of Test House was 23.9 kWh/m^{2}a, while the criterion in this region (zone 4, see Figure 1-9) is 128 kWh/m^{2}a (see Table 1-1). The Test House clearly has far better energy performance than the ones in accordance with this standard. Buildings with the envelope system can greatly contribute to the reduction of energy consumption in the Japanese construction industry.

The insulation thickness of Test House (18 cm) needs to be verified by the optimization model. When applying the climatic data of Nagoya (which is the city out of the 8 selected cities nearest to the construction site of Test House), the retail price of the wood fiber insulation provider, the service life of 30 years, an interest rate of 2% and an electricity price increase of 4%, the optimal 10% range was 10-13 cm (see Figure 5-11(e)). The price of the wood fiber insulation board actually has a special discount of 64% since this is a pilot project, and the optimal 10% range becomes 10-17cm when this special price is applied. Even though the designed thickness is still a little larger than the 10% optimal range, it can be said that the insulation design was more or less appropriate. (The critical reason for using 18 cm of insulation was that this building will be certified with MINERGIE-P® standard, which is modified for Japanese conditions and it was necessary to prioritize the reduction of energy consumption.) Nevertheless, the design of Test House should not be taken as a general example of an optimized building under Japanese conditions when such a price discount is not taken into account.

With regard to the utilization of domestic wood resources, the potential of CO_2 emission reduction when producing the cross laminated timber element with Japanese domestic wood resources was carried out as a supplemental study. As a result, it was shown that a building with domestic wood cross laminated timber has about a 65% reduction of CO_2 emission compared to the conventional post and beam and 2x4 buildings, which consist mainly of imported woods and wood-based materials. The detail of this calculation is presented in Appendix D.

In addition, the sustainability evaluation of Test House was carried out by the Japanese sustainability evaluation tool for buildings (see 1.1.3 and 1.2.4.1), which reflects the conditions and thinking of the Japanese construction industry. It was concluded that the advantage of the envelope system cannot be emphasized by CASBEE. This is because the evaluation method is assuming the application of buildings with conventional features. This conflict might represent a less social acceptance of the technology. The advantage of the system should be well explained to users and practitioners in order to avoid misunderstandings derived by conservative thinking. The detail of CASBEE evaluation is presented in Appendix E.

In order to improve the reliability and general versatility of the models proposed in this thesis, the following points should be further considered.

Regarding the transient heat and moisture transfer model, the major shortcoming is that the reliability of the model on the wind driven rain impact of the façade is fairly low as mentioned in 2.2.1. Considering the two realistic façade solutions (one with a combination of cladding and an air layer and one with plaster), the influence of wind driven rain is definitely critical in the case with plaster. The possibilities are that (1) a different model capable of modeling the influence of wind driven rain is employed and (2) a plaster is used which ensures that no liquid water penetration reaches the substrate of the plaster (wood fiber insulation). As for solution (1), no such (commercial) tool available yet. A new tool should be developed for this solution. As for solution (2), an appropriate plaster should be tested under the weather conditions of subtropical regions (especially considering the wind driven rain of typhoons and the longer duration of the humid season). In addition to the consideration of wind driven rain, the setting of an exterior boundary condition of the cladding system also leaves an open point. Depending on the material of the cladding and air layer thickness, the air in the air layer might be significantly affected (warmed up) by the temperature of the cladding itself, which is directly exposed to solar radiation. This would cause airflow upwards in the air layer. If this were to happen, the convective transfer of heat and moisture of the insulation surface becomes less resistant (in daytime) and eventually lessens the risk of moisture accumulation inside the wall. Since the simulations in this thesis (see Chapter 3) were modeled facing north, such an affect is assumed to be negligible. Nevertheless, this should be further investigated by *in-situ* measurements with an actual building.

Regarding the whole building heat and moisture balance model, the major shortcoming is the limited granularity of the building modeled. Since the building is translated into one volume in the tool employed, the air and moisture flow inside the building cannot be taken into account. As for the heat distribution, it is fair to assume that there is no big temperature gradient in a building that is entirely well insulated and airtight and is regulated by mechanical ventilation with highly efficient heat recovery. The interesting point is whether or not the moisture dispersion from bathroom and kitchen would cause a significant gradient of humidity in the whole building. In this case the model, which is currently limited to one volume, should be expanded to a multi-volume model capable of simulating the moisture dispersion driven by airflow and diffusion among the volumes (rooms). This should be further investigated by *in-situ* measurements with an actual building.

Also, a dehumidification load should be calculated in the whole building heat and moisture balance model; because the Test House (see Chapter 4) was designed to have a radiator-type dehumidifier, no dehumidification load was accounted for in the simulation. Even though this is an ideal solution in terms of energy consumption, the active dehumidification should be considered when the moisture load exceeds its dehumidifying capacity of maintaining a comfortable and moisture-risk-free indoor condition.

Regarding the economic and ecological optimization model, the most critical point is how the service life of the insulation is defined, taking into account the actual longevity of the material. The insulation material itself would last a lifetime as long as it is kept dry and shielded from UV rays. The challenge then is how to model the probability of the occurrence of such damages due to extreme weather events or imperfect craftwork. The cost of maintenance and dismantling should also be considered based on the actual maintenance plan. Also, the heating and cooling energy in the model should include other strategies run by other energy carriers such as oil or wood pellets in order to enhance the versatility of the model. Last but not least, the input price of the material should carefully reflect the condition of local markets. The actual market price of building components is often different to a certain extent from the retail price offered by the producers in the Japanese construction industry, and furthermore this price can differ between regions. This point must be considered when designing and modeling the optimal insulation thickness of an actual building to be constructed.

In order to further enhance the overall modeling, quantification and optimization of not only the lifecycle environmental impact and cost, but also the social aspect of acceptance by inhabitants should be integrated in the models. The air acceptability index introduced in Chapter 3 might be a sound way to accomplish this. In this case, the contribution of measures other than insulating, heating/cooling and dehumidification (window opening, shading and so on) should be investigated regarding its contribution to air acceptability. The challenge is how the trade-off between passive measures and active measures in terms of energy consumption and air acceptability is dealt with.

Furthermore, the applicability of the envelope system to other regions with similar climatic conditions (see Figure 1.1) should be evaluated with appropriate designs, considering the user behavior, local climate, local economic situation and local energy supply. User behavior, such as preferred room temperature/humidity and preferred heating/cooling method, should especially be thoroughly reflected upon to ensure the acceptability of the technology. Additionally, the building component of each layer may be reconsidered taking into account the availability of local resources and products.

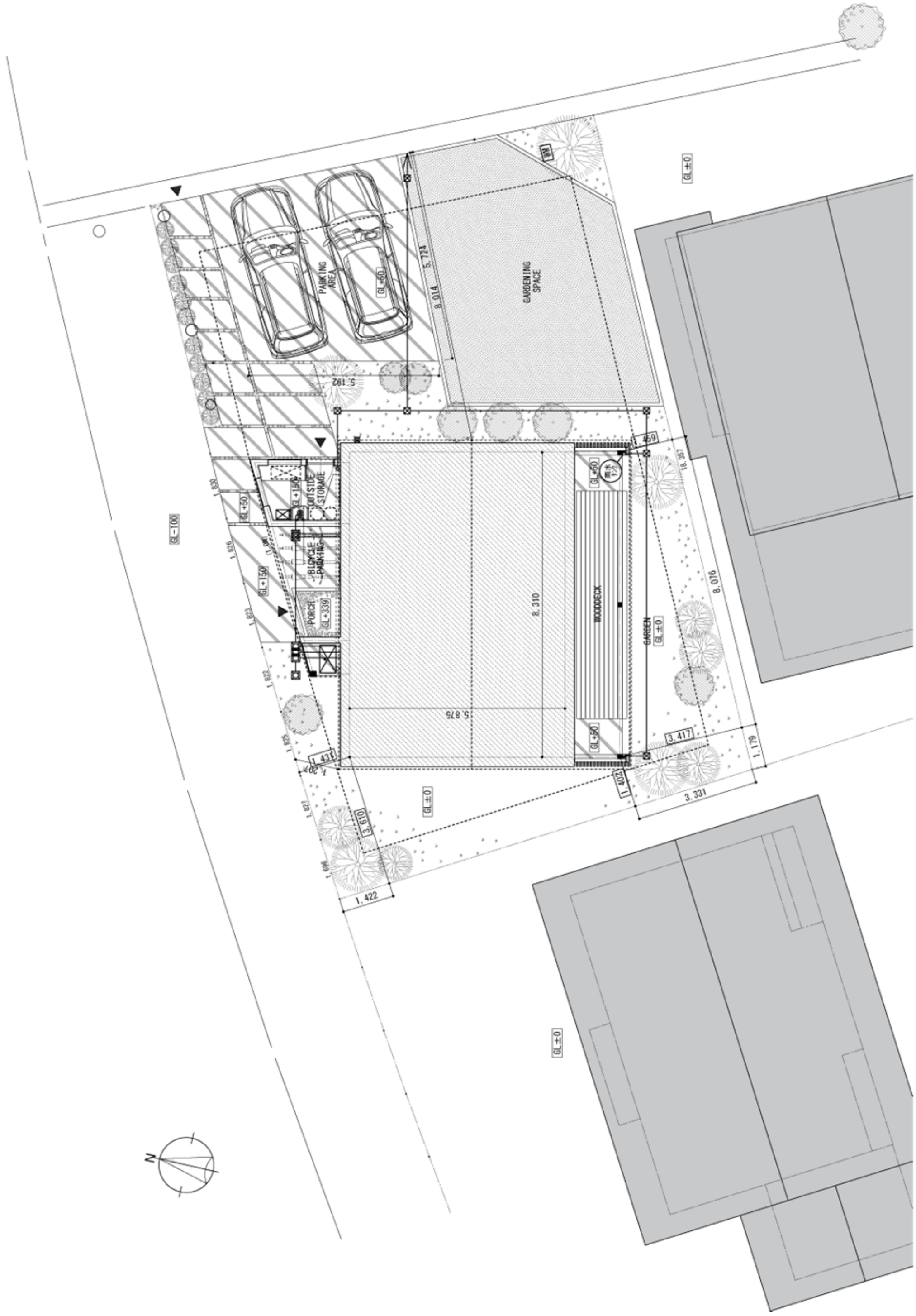
The overall building physics and optimization model proposed in this thesis has great potential for application with other construction method as well given the versatility of modeling multi-layered building components within both the one-dimensional transient heat and moisture transfer model and the whole building heat and moisture balance model. The only changes required in the framework of the model are the envelope model, in which each layer should be modified with appropriate thicknesses and material properties, and subsequently the environmental impact coefficient of the LCA indicators according to the material selection.

Last of all, the whole building heat and moisture balance model will be validated with empirical data from a pilot building (Test House) to be constructed in Ohmihachiman city in May 2013. In this pilot building, the temperature and humidity of the main rooms (the living room, one of the bedrooms and the attic space) will be measured for at least one year with the actual inhabitants. The temperature and humidity inside an external wall and the roof (the wall of the living room, the room next to the bathroom and the roof on north side) will also be measured by sensors installed on the exterior side of the insulation, inside the insulation, between the insulation and cross laminated timber element, between cross laminated timber element and clay board finishing and on the interior side of the clay board. The measured temperature/humidity of the rooms will be applied to validate the whole building heat and moisture model. The measurements of the walls and the roof will be applied to validate the one-dimensional transient heat and moisture transfer model. In the case that major discrepancies between the predicted and measured values are observed, the model will be modified.

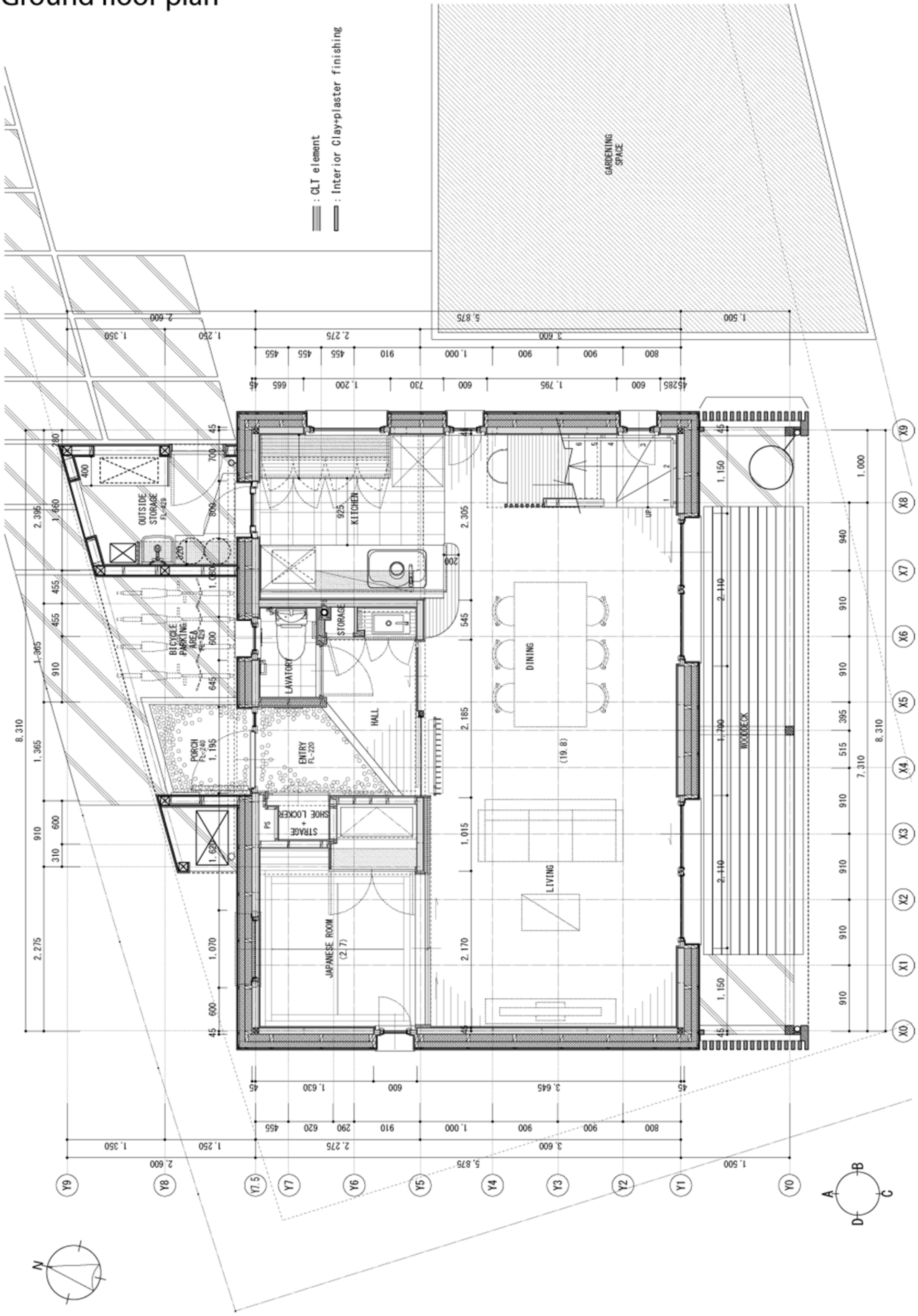
APPENDIX

Appendix A - General drawings of the Test House

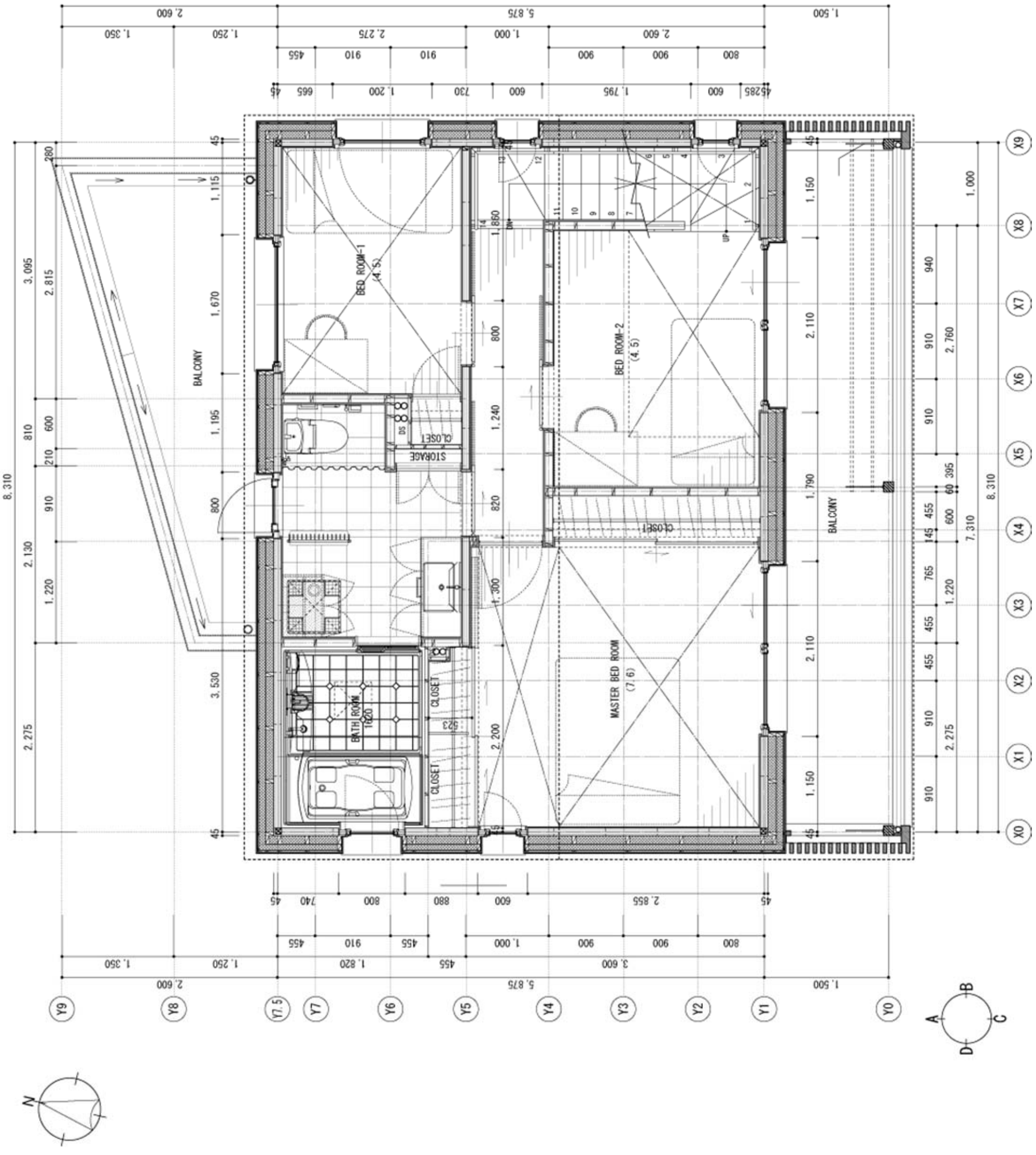
Site plan



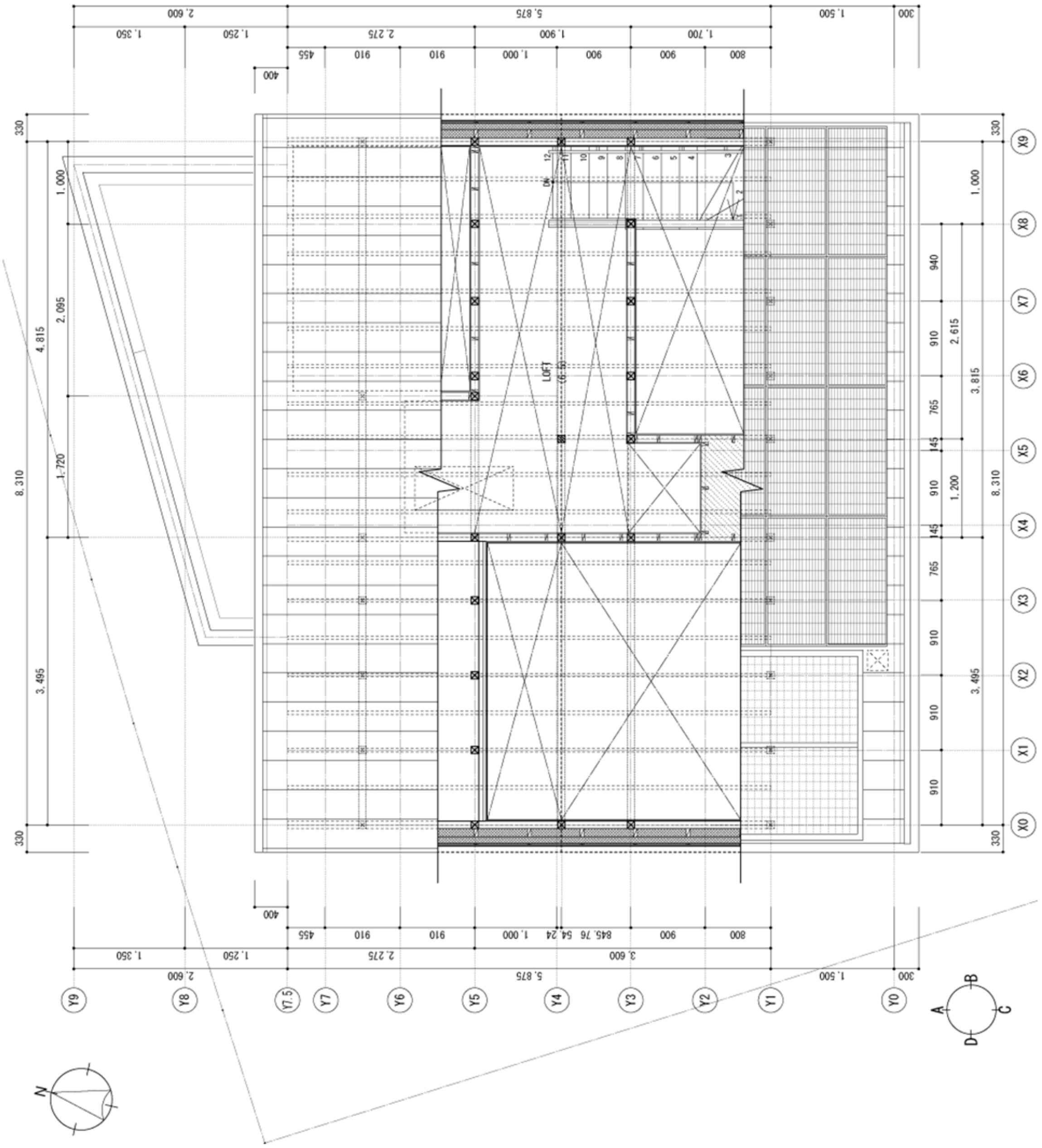
Ground floor plan



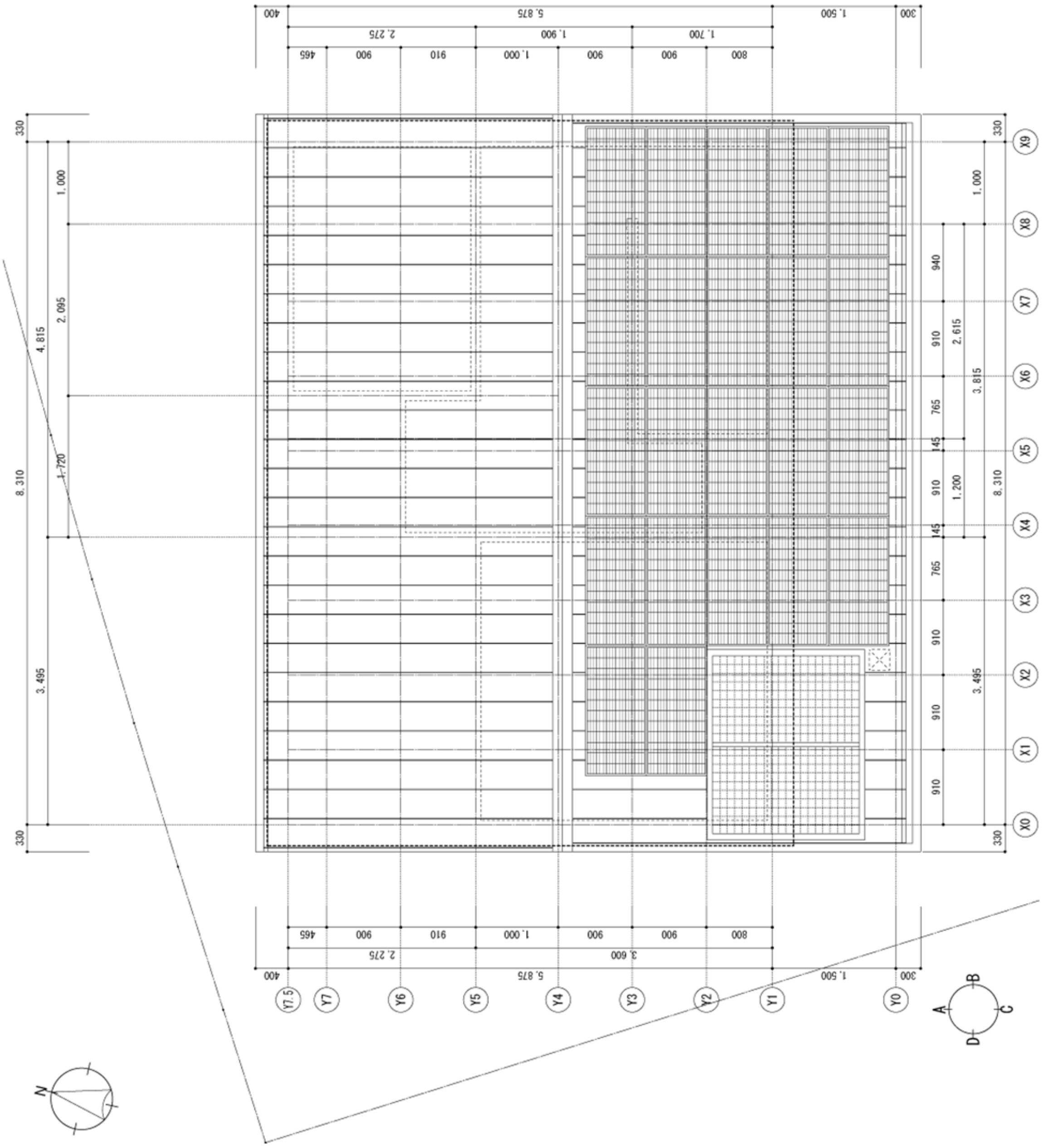
1st floor plan



Loft floor plan



Roof plan

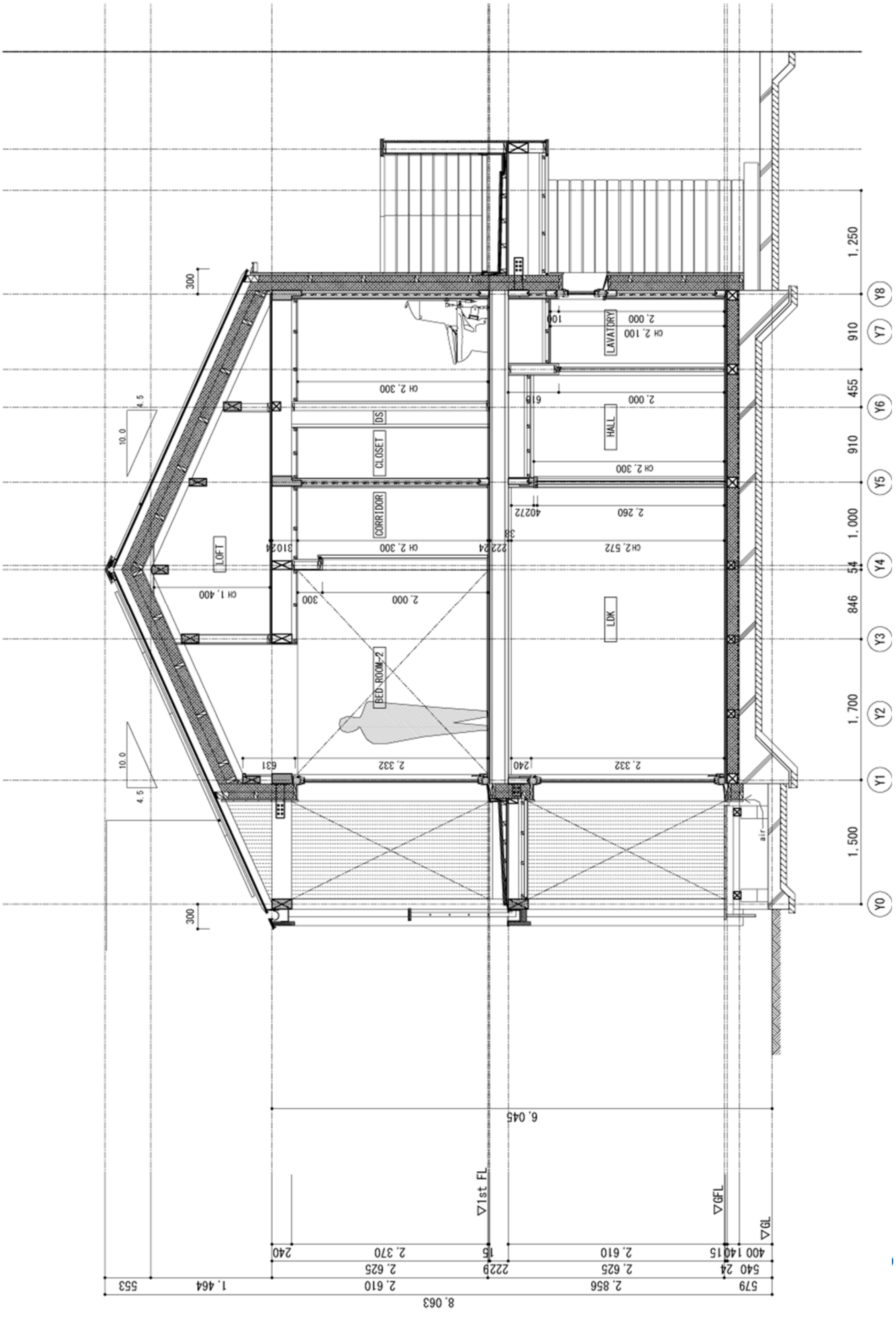


X0
X1
X2
X3
X4
X5
X6
X7
X8
X9
Y0
Y1
Y2
Y3
Y4
Y5
Y6
Y7
Y7.5
8,310
4,815
3,495
2,095
1,720
1,000
330
940
910
765
145
2,615
3,815
1,200
400
5,875
1,500
300
2,275
1,900
1,700
465
900
910
1,000
800
3,600
N
A
B
C
D

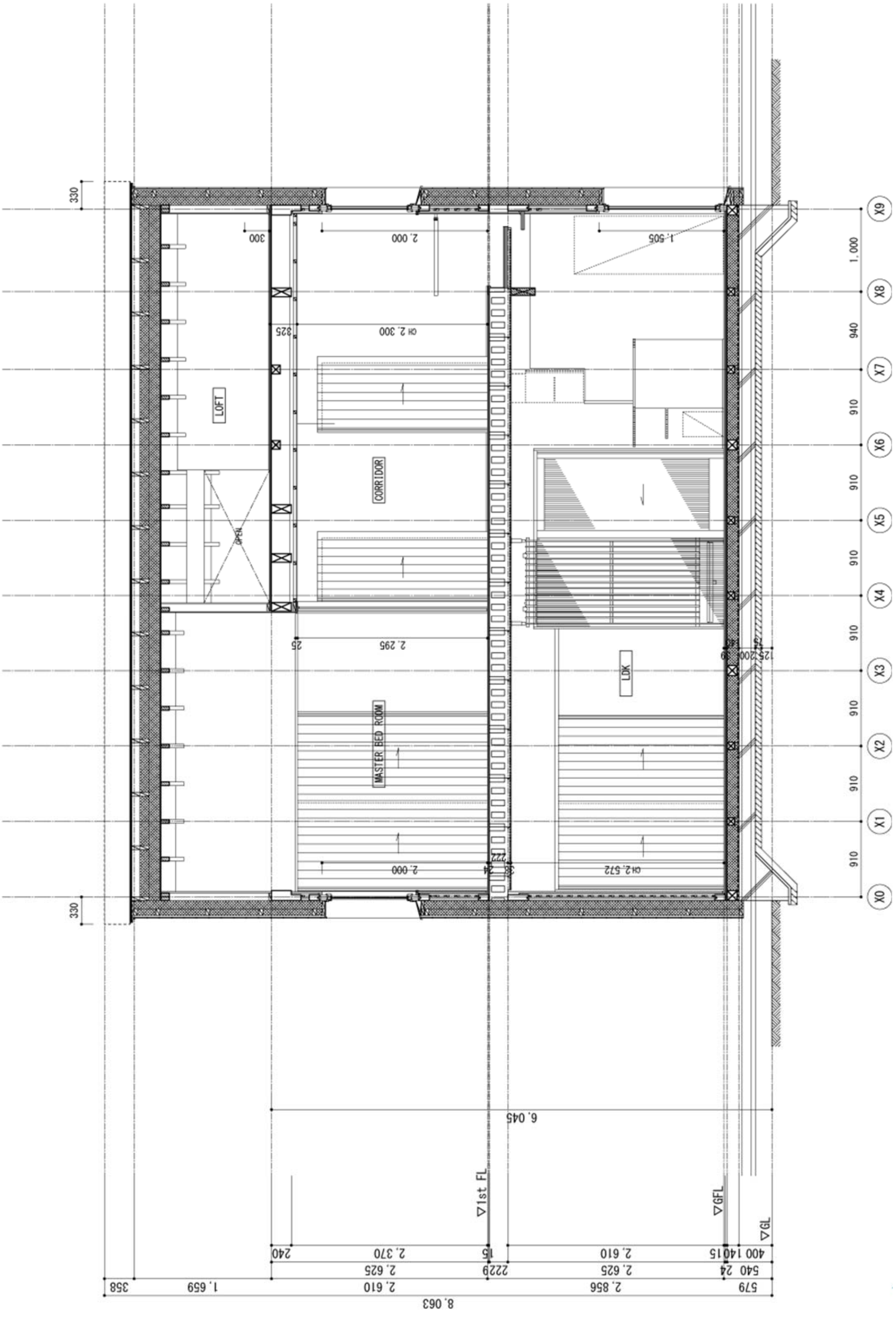
Elevation


EAST ELEVATION
WEST ELEVATION
SOUTH ELEVATION
NORTH ELEVATION
400
300
330
10.0
4.5
OPEN
6,045
8,063

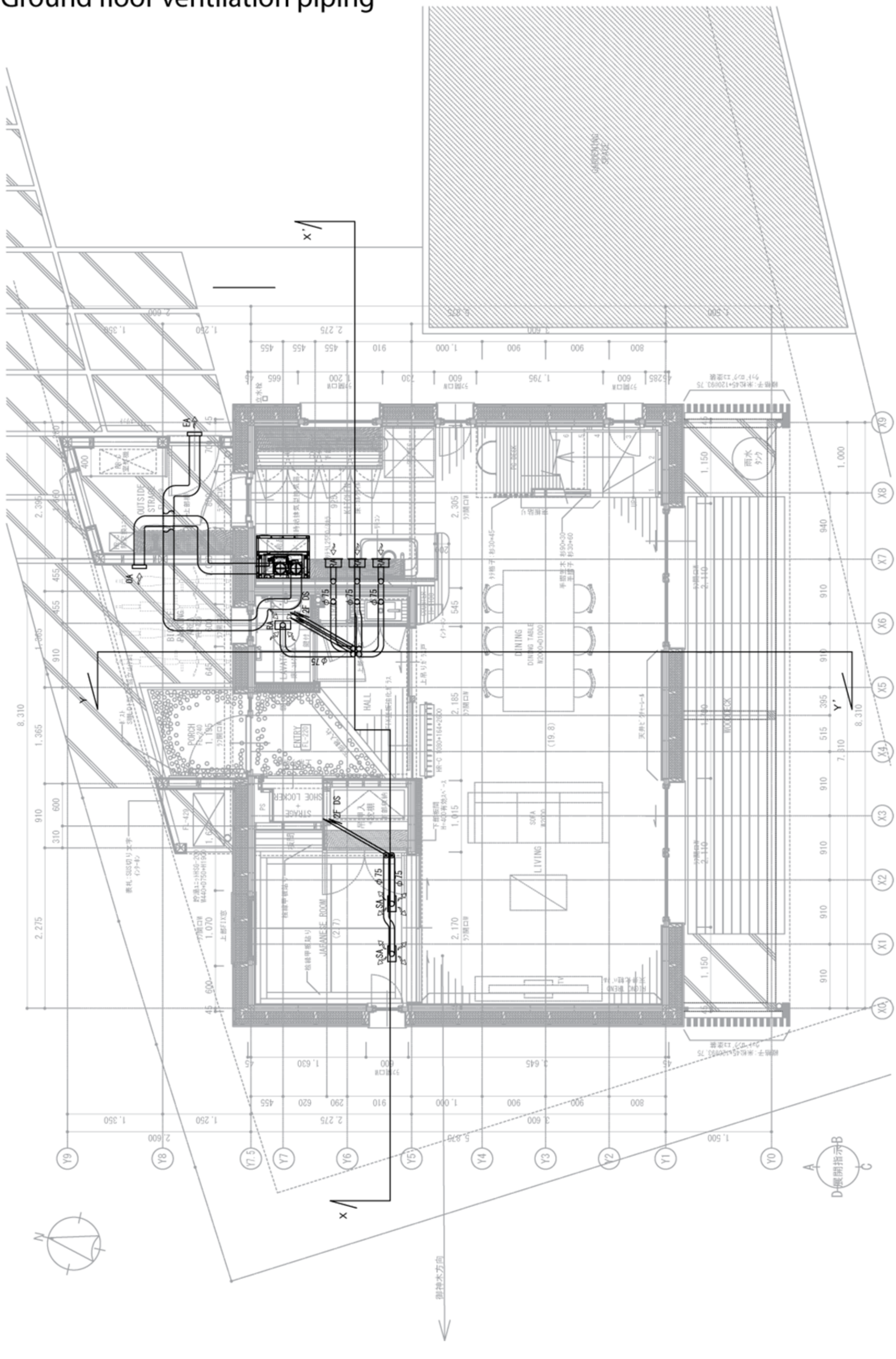
Sectional detail 1



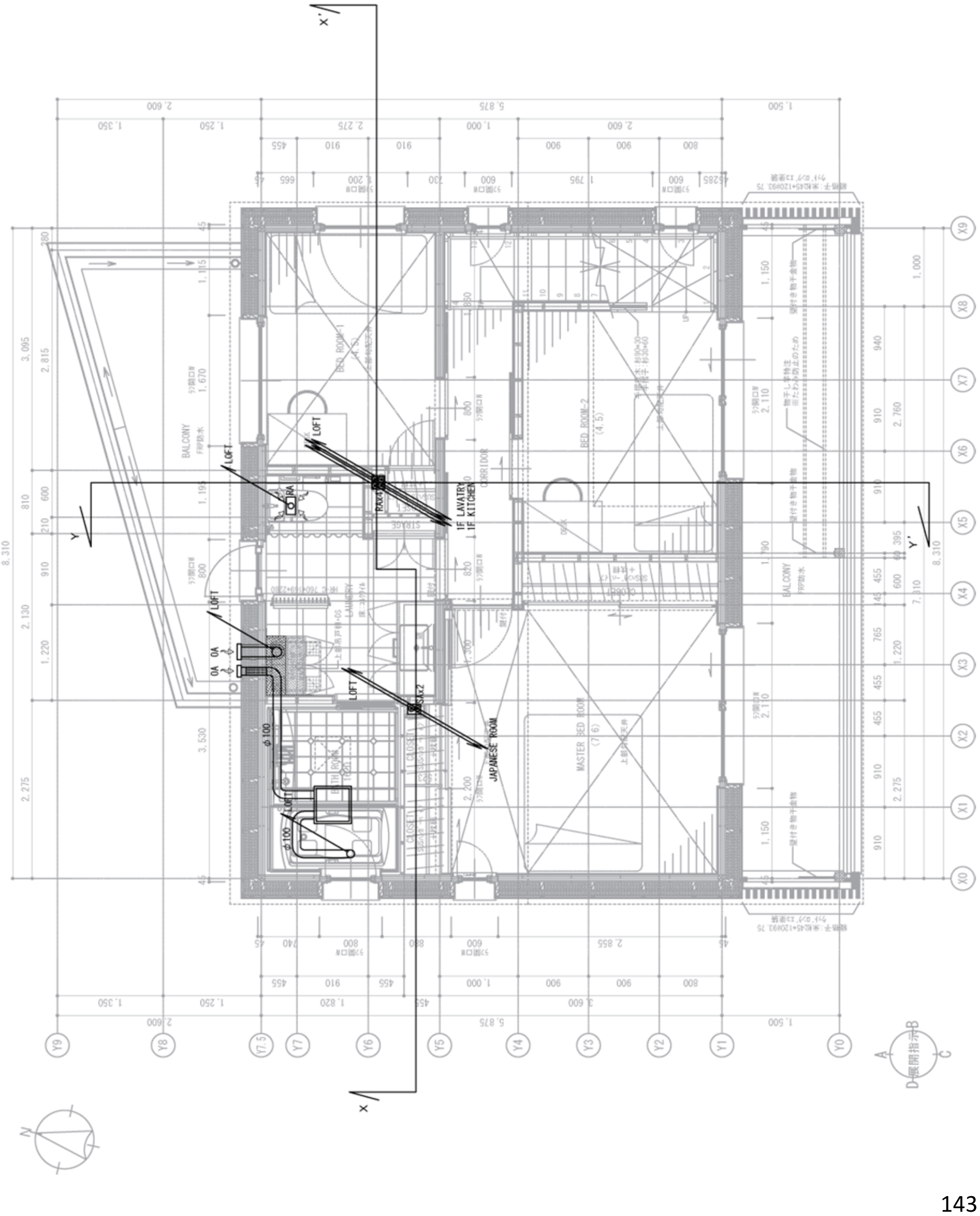
Sectional detail 2



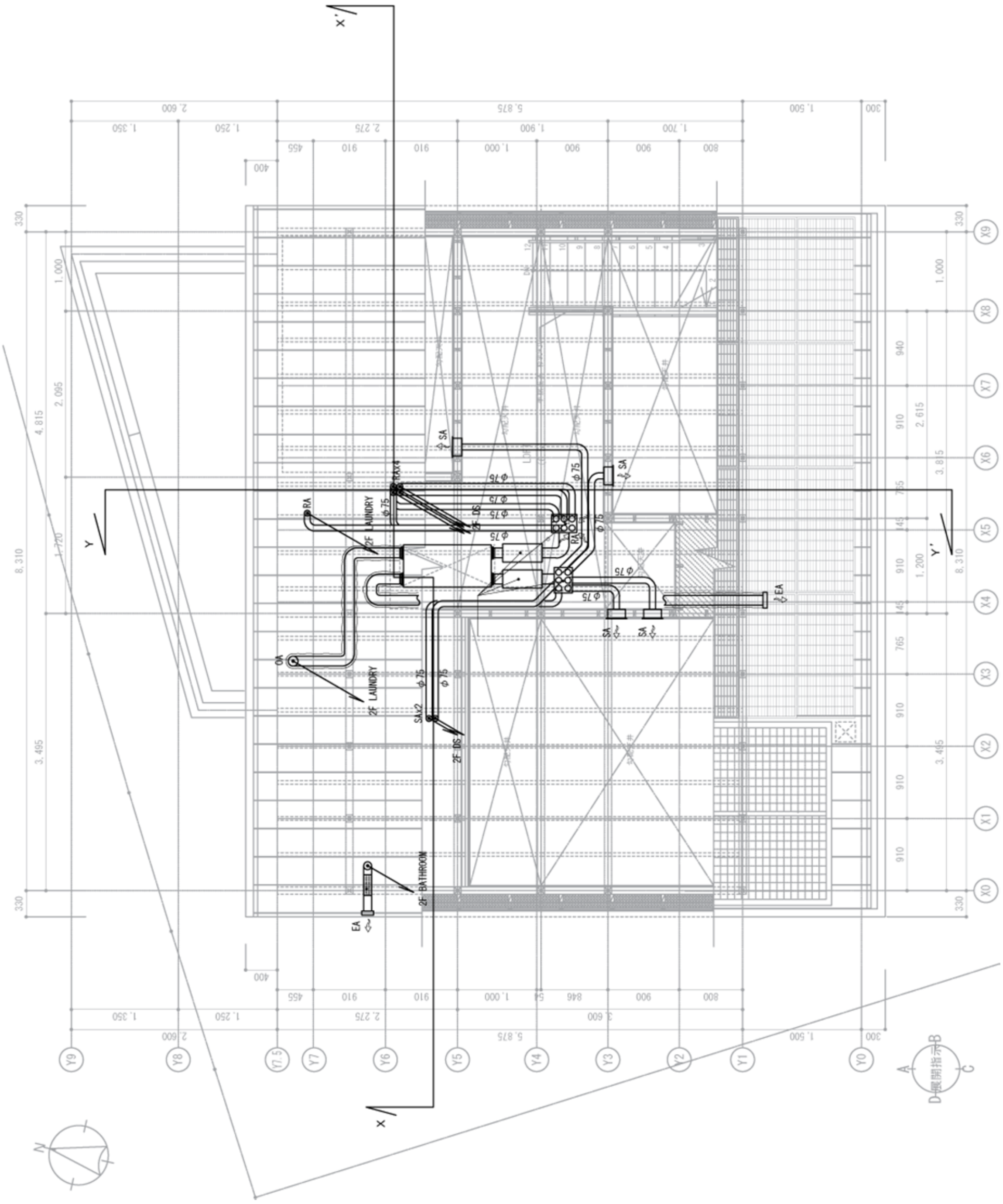
Ground floor ventilation piping



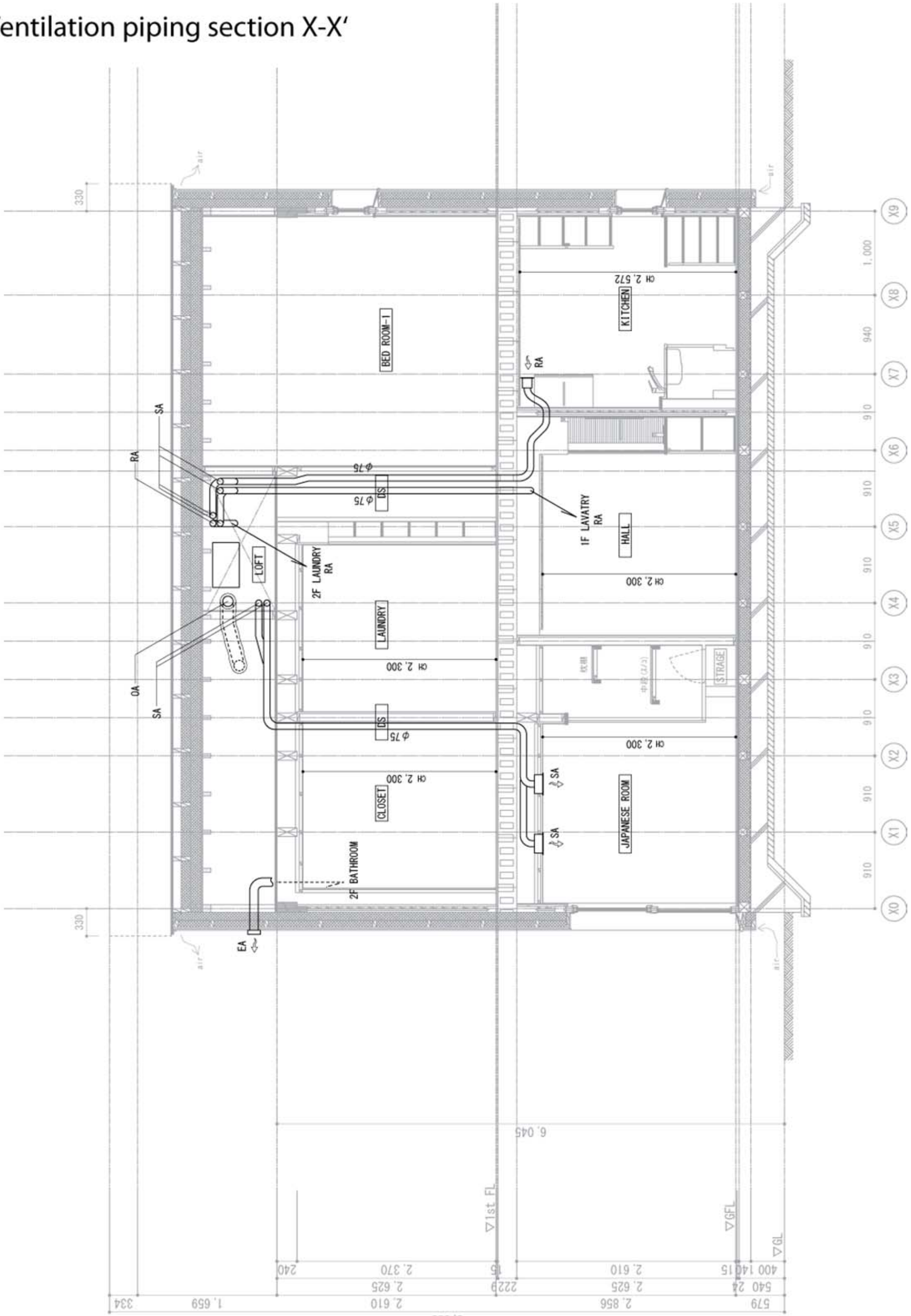
1st floor ventilation piping



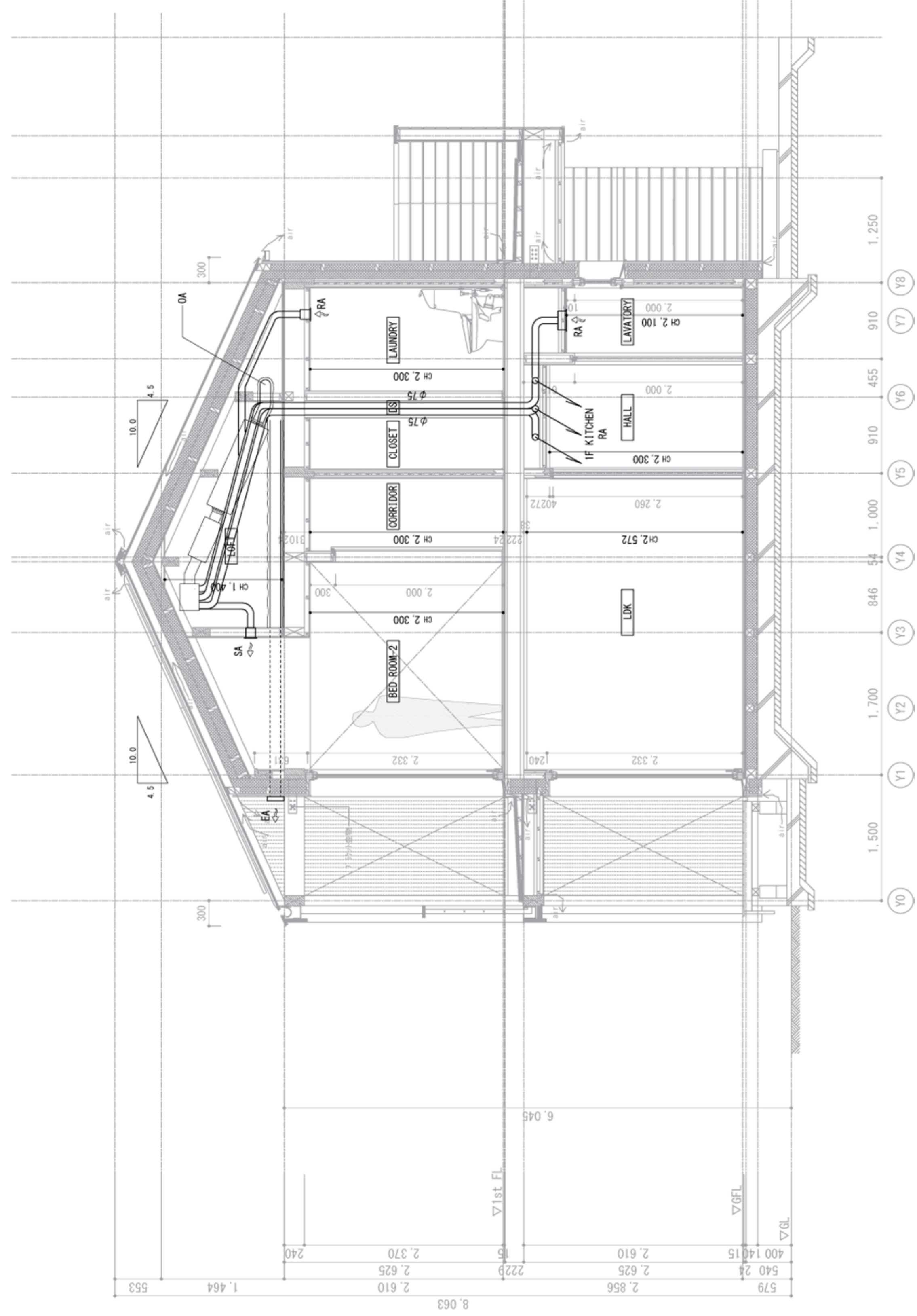
Loft ventilation piping



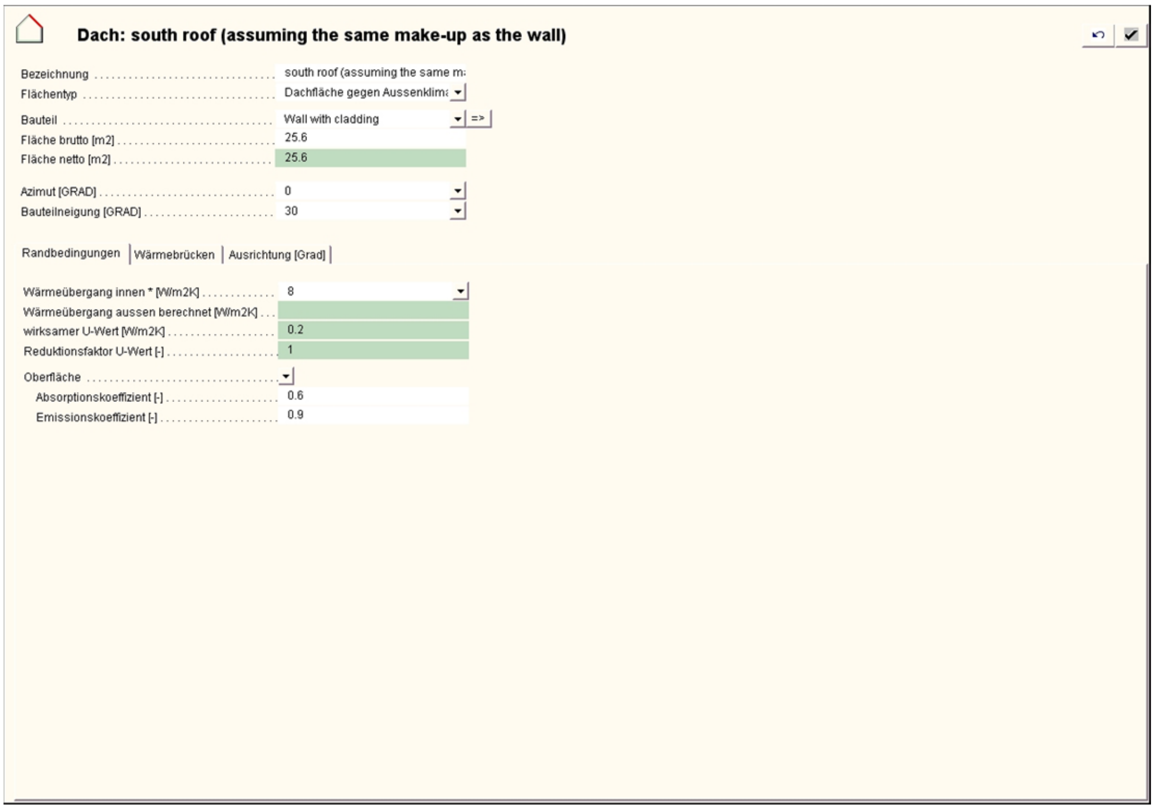
Ventilation piping section X-X‘



Ventilation piping section Y-Y'

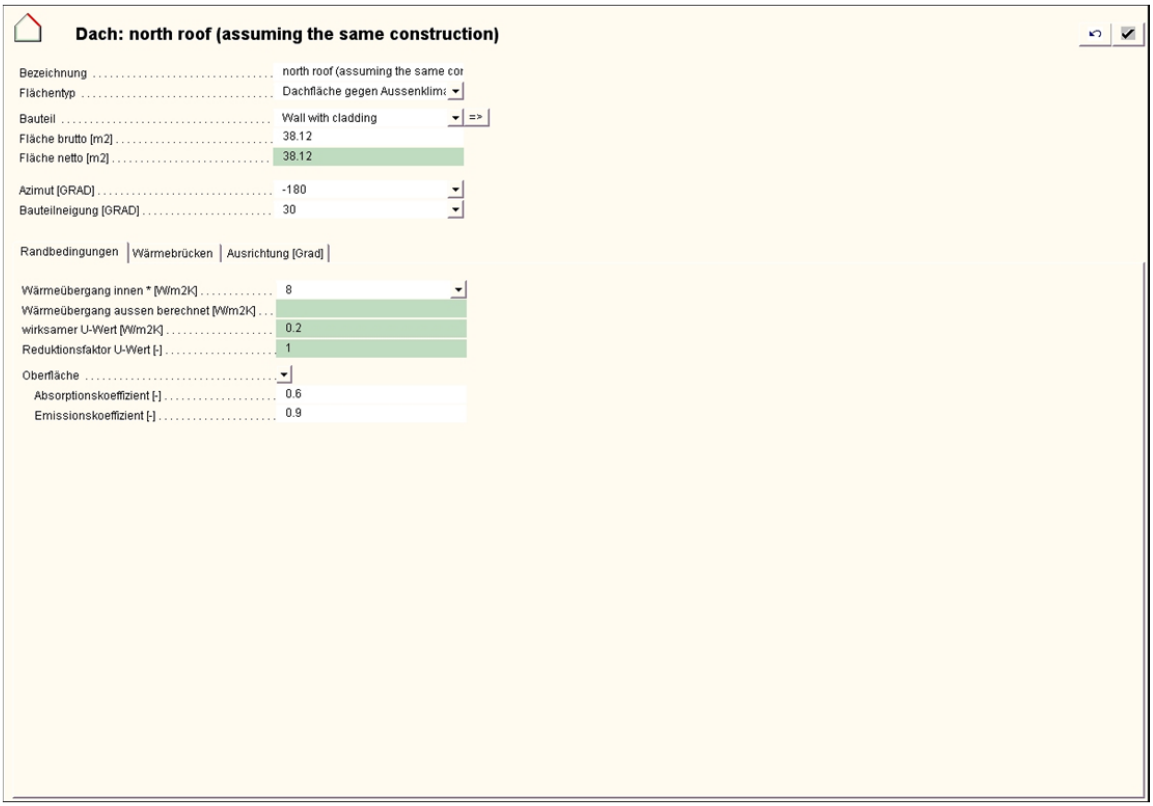


Appendix B - Input for Helios simulation



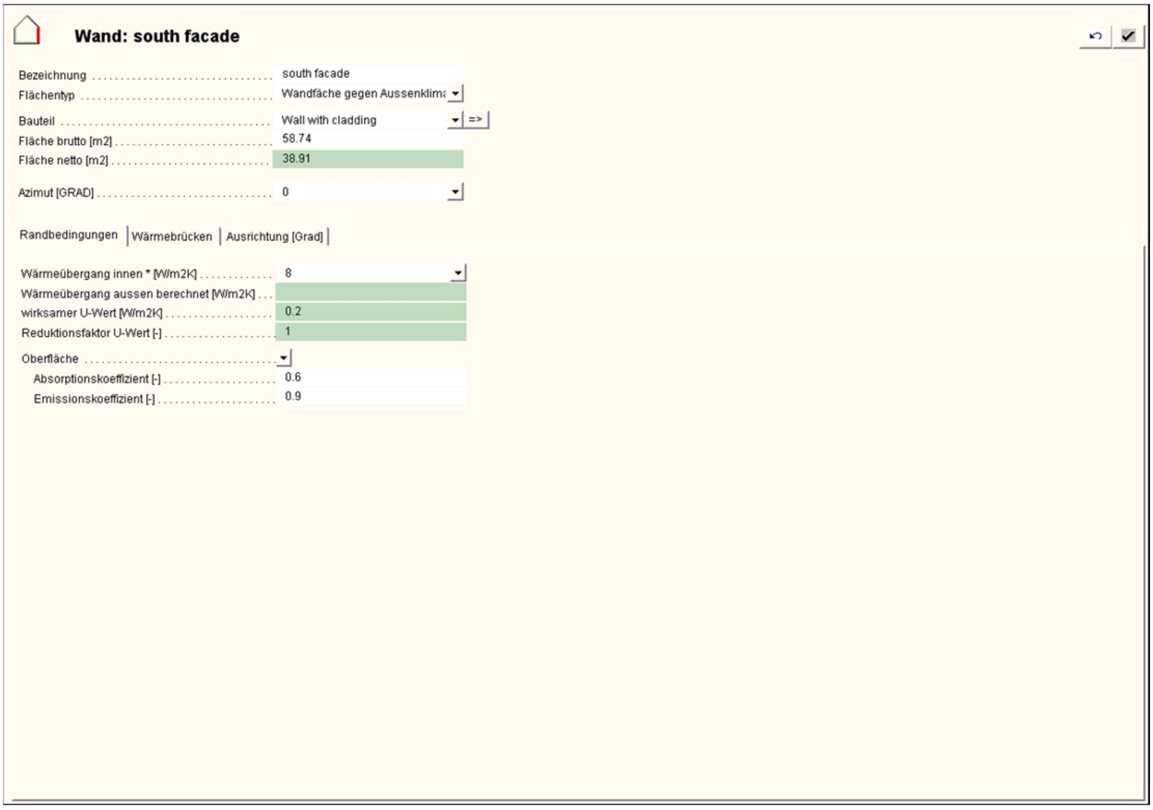
Dach: south roof (assuming the same make-up as the wall)

Bezeichnung	south roof (assuming the same m
Flächentyp	Dachfläche gegen Aussenklima
Bauteil	Wall with cladding
Fläche brutto [m2]	25.6
Fläche netto [m2]	25.6
Azimut [GRAD]	0
Bauteilneigung [GRAD]	30
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



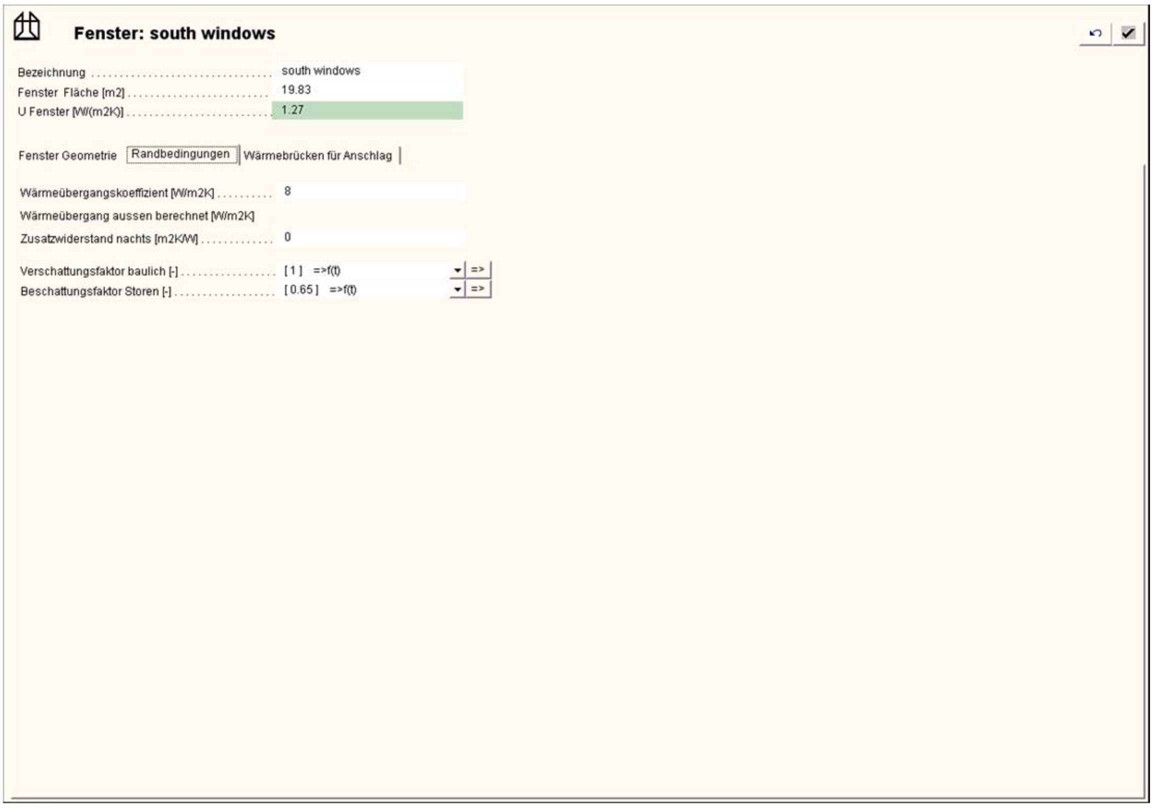
Dach: north roof (assuming the same construction)

Bezeichnung	north roof (assuming the same cor
Flächentyp	Dachfläche gegen Aussenklim:
Bauteil	Wall with cladding
Fläche brutto [m2]	38.12
Fläche netto [m2]	38.12
Azimut [GRAD]	-180
Bauteilneigung [GRAD]	30
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



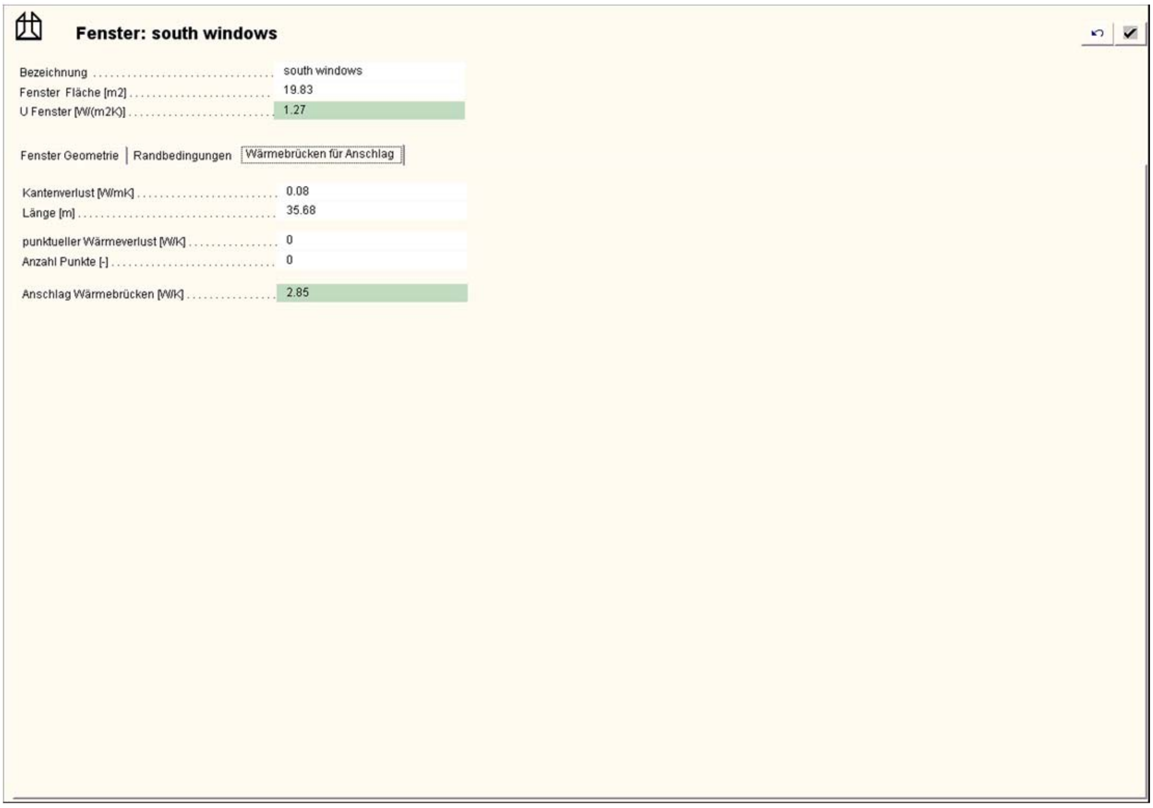
Wand: south facade

Bezeichnung	south facade
Flächentyp	Wandfläche gegen Aussenklim:
Bauteil	Wall with cladding
Fläche brutto [m2]	58.74
Fläche netto [m2]	38.91
Azimut [GRAD]	0
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



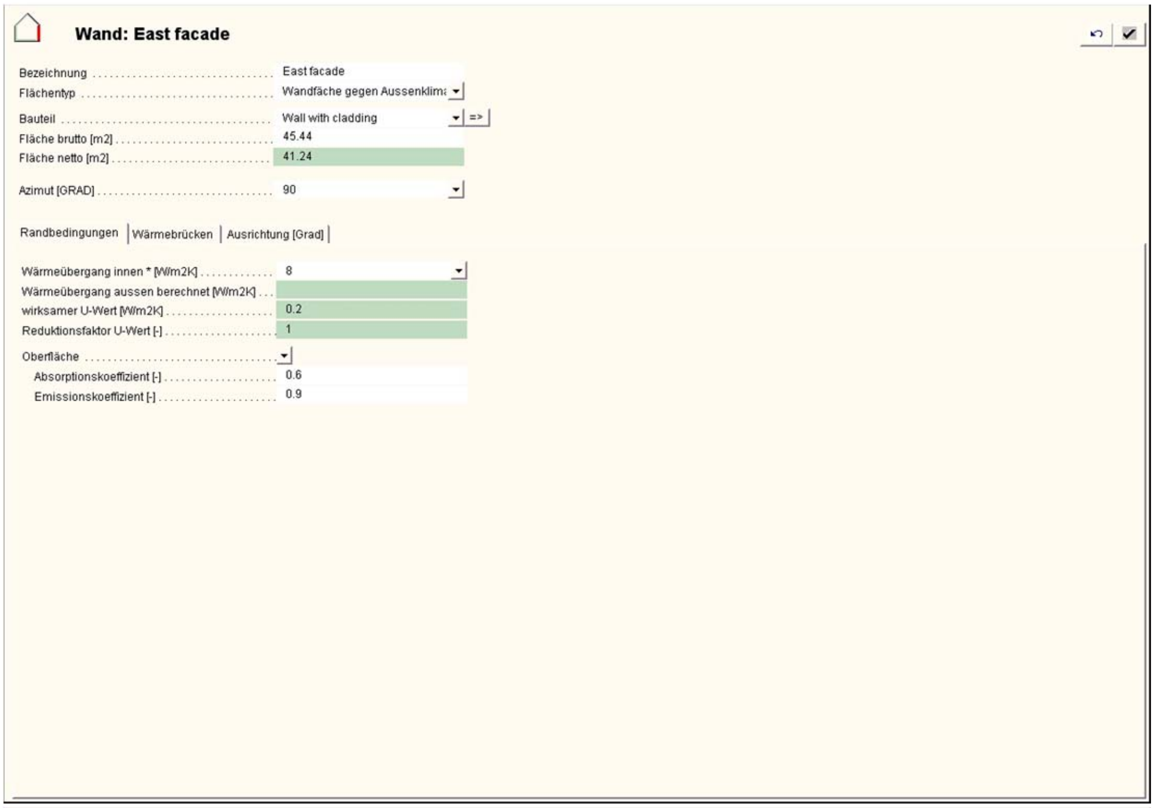
Fenster: south windows

Bezeichnung	south windows
Fenster Fläche [m2]	19.83
U Fenster [W/(m2K)]	1.27
Wärmeübergangskoeffizient [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
Zusatzwiderstand nachts [m2K/W]	0
Verschattungsfaktor baulich [-]	[1] =>f(t)
Beschattungsfaktor Storen [-]	[0.65] =>f(t)



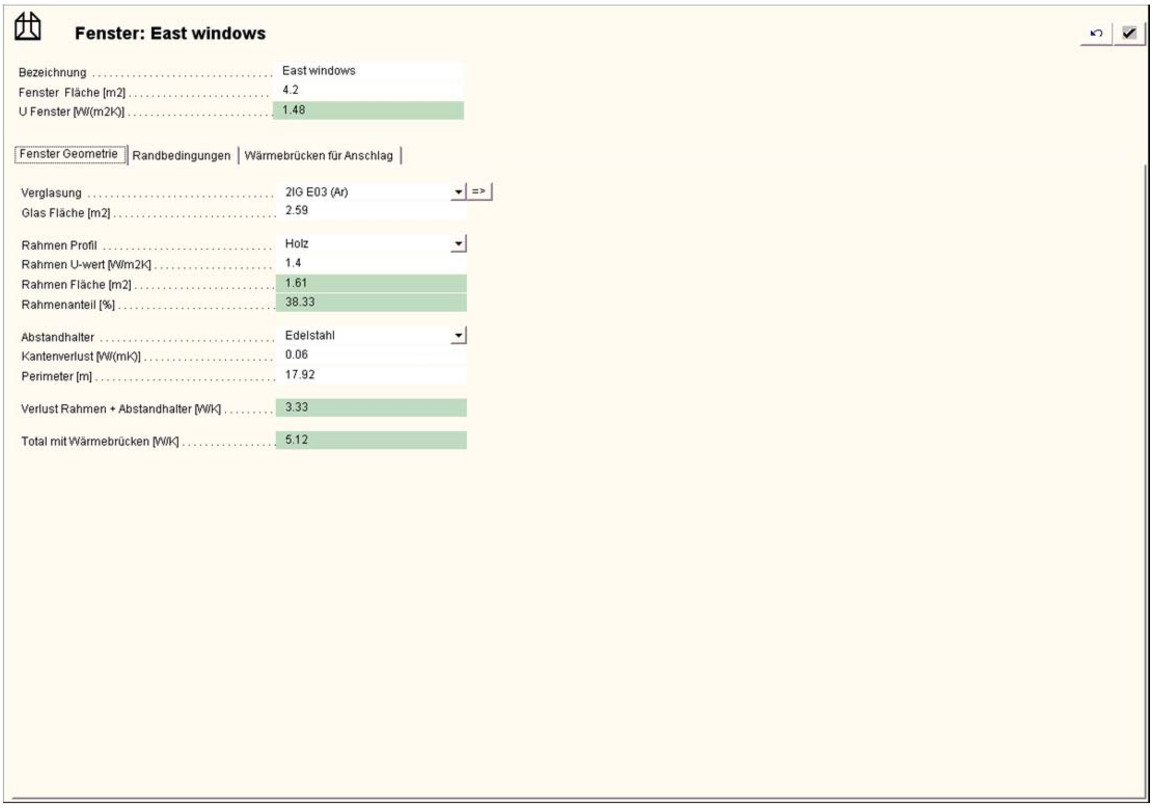
Fenster: south windows

Bezeichnung	south windows
Fenster Fläche [m2]	19.83
U Fenster [W/(m2K)]	1.27
Kantenverlust [W/mK]	0.08
Länge [m]	35.68
punktueller Wärmeverlust [W/K]	0
Anzahl Punkte [-]	0
Anschlag Wärmebrücken [W/K]	2.85



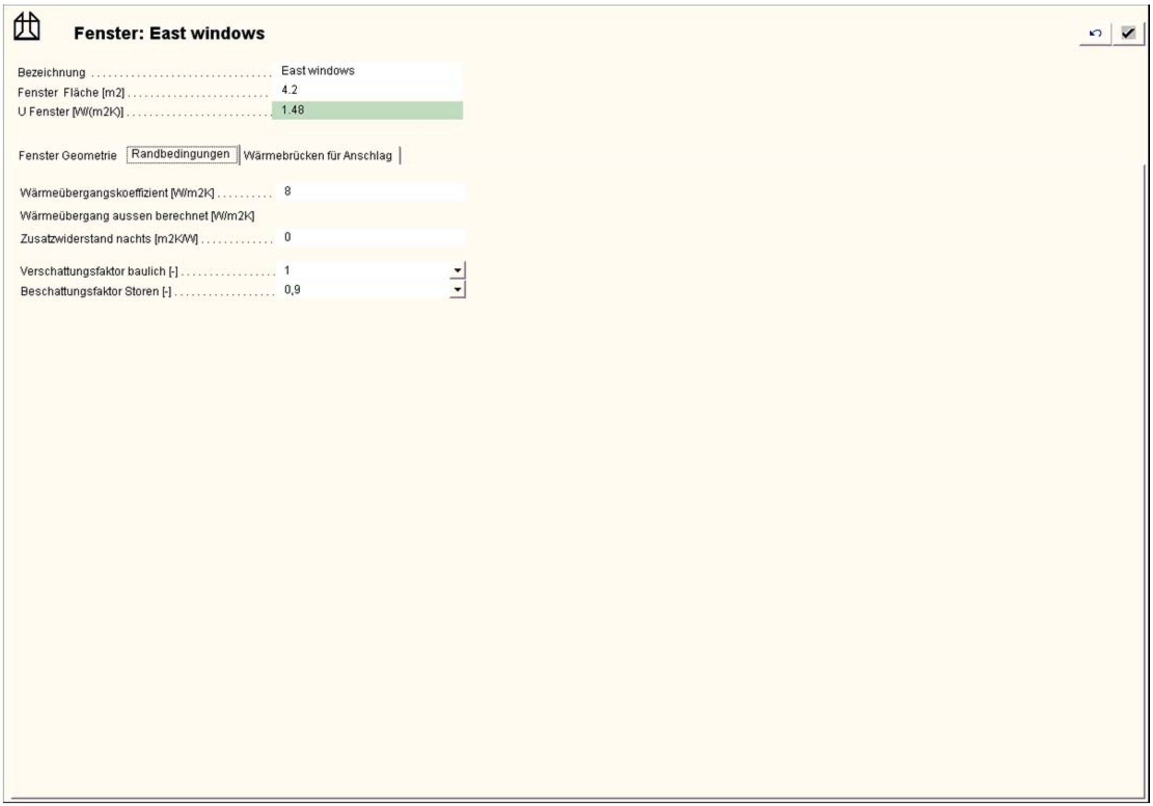
Wand: East facade

Bezeichnung	East facade
Flächentyp	Wandfäche gegen Aussenklim:
Bauteil	Wall with cladding
Fläche brutto [m2]	45.44
Fläche netto [m2]	41.24
Azimut [GRAD]	90
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



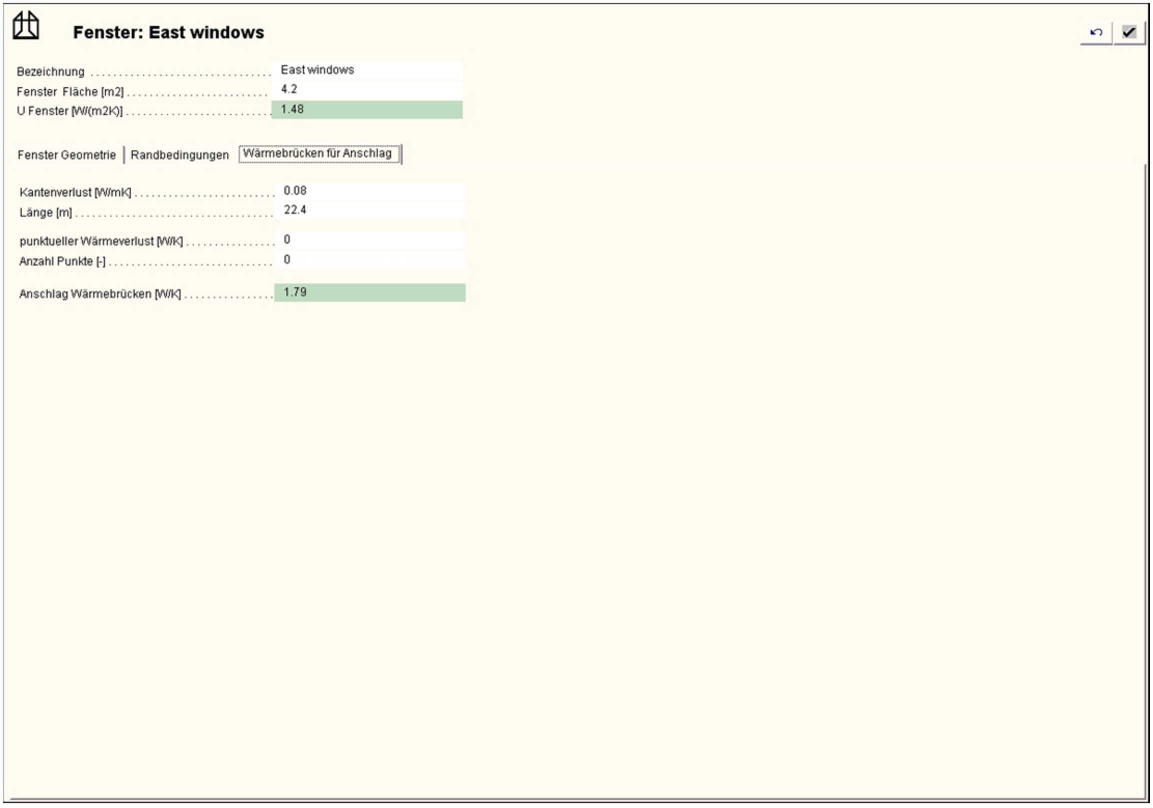
Fenster: East windows

Bezeichnung	East windows
Fenster Fläche [m2]	4.2
U Fenster [W/(m2K)]	1.48
Verglasung	2IG E03 (Ar)
Glas Fläche [m2]	2.59
Rahmen Profil	Holz
Rahmen U-wert [W/m2K]	1.4
Rahmen Fläche [m2]	1.61
Rahmenanteil [%]	38.33
Abstandhalter	Edelstahl
Kantenverlust [W/(mK)]	0.06
Perimeter [m]	17.92
Verlust Rahmen + Abstandhalter [W/K]	3.33
Total mit Wärmebrücken [W/K]	5.12



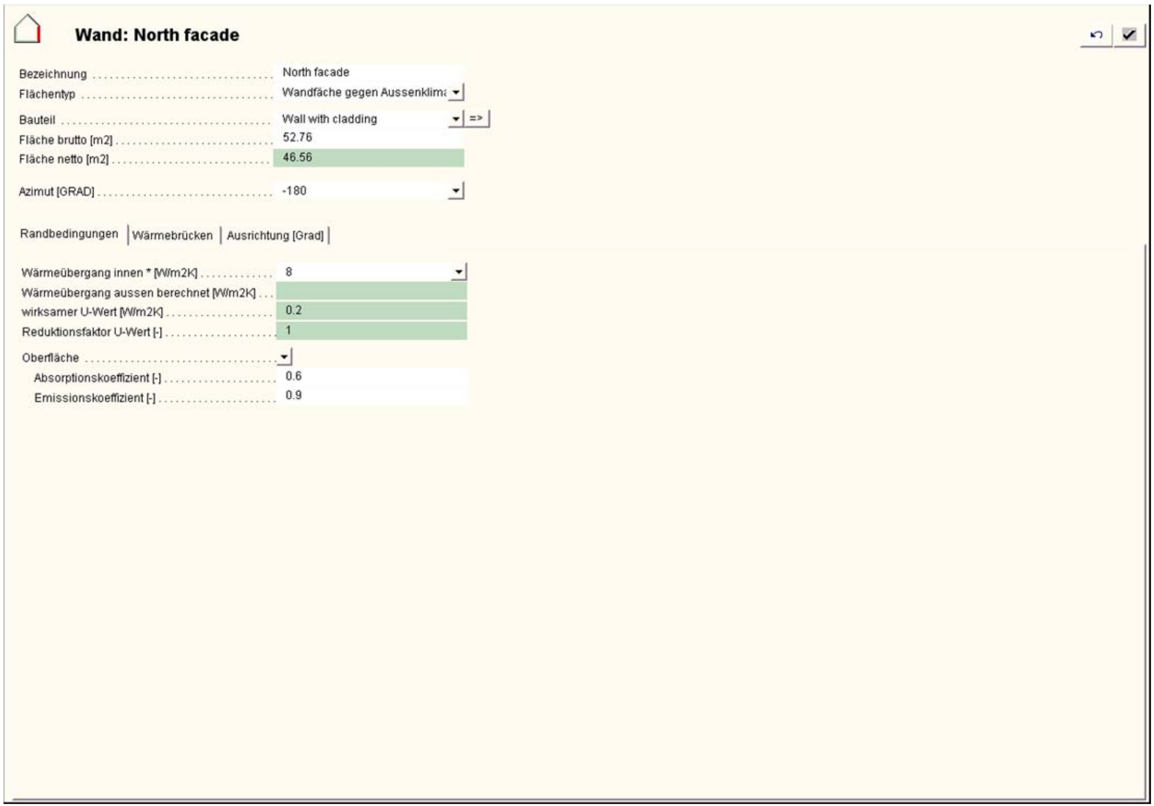
Fenster: East windows

Bezeichnung	East windows
Fenster Fläche [m2]	4.2
U Fenster [W/(m2K)]	1.48
Wärmeübergangskoeffizient [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
Zusatzwiderstand nachts [m2K/W]	0
Verschattungsfaktor baulich [-]	1
Beschattungsfaktor Storen [-]	0,9



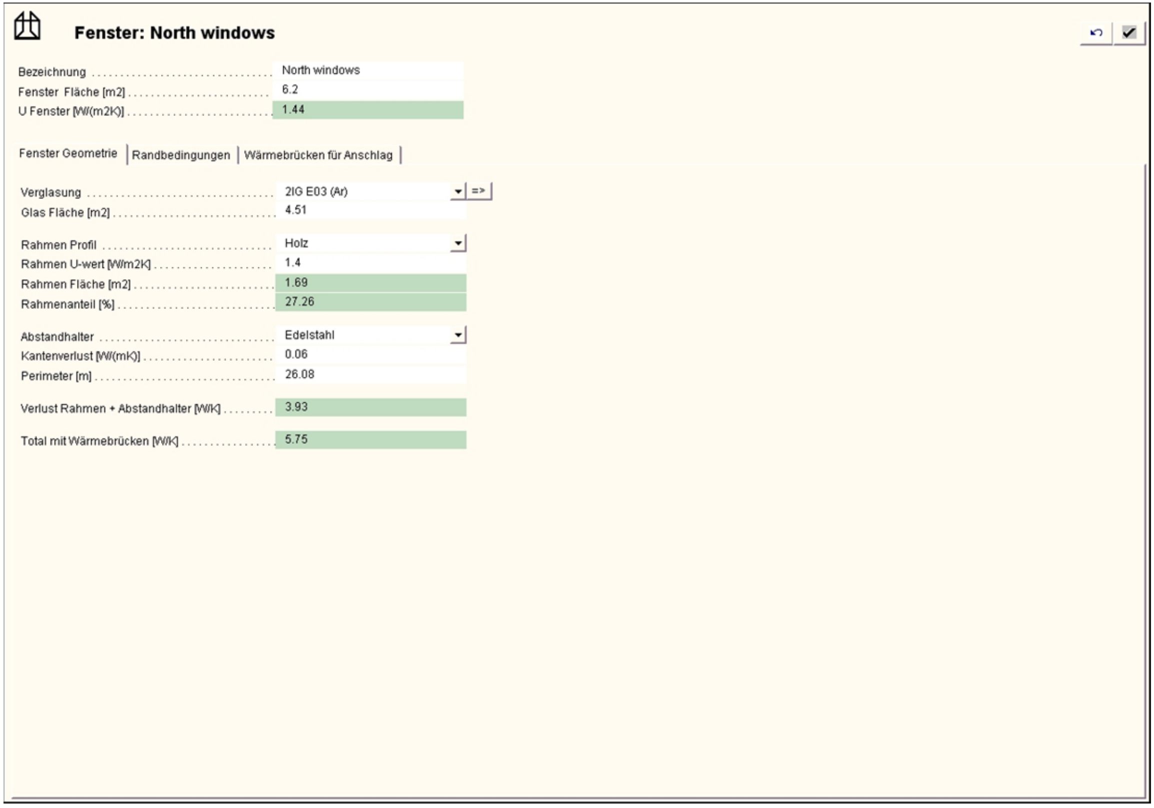
Fenster: East windows

Bezeichnung	East windows
Fenster Fläche [m2]	4.2
U Fenster [W/(m2K)]	1.48
Kantenverlust [W/mK]	0.08
Länge [m]	22.4
punktueller Wärmeverlust [W/K]	0
Anzahl Punkte [-]	0
Anschlag Wärmebrücken [W/K]	1.79



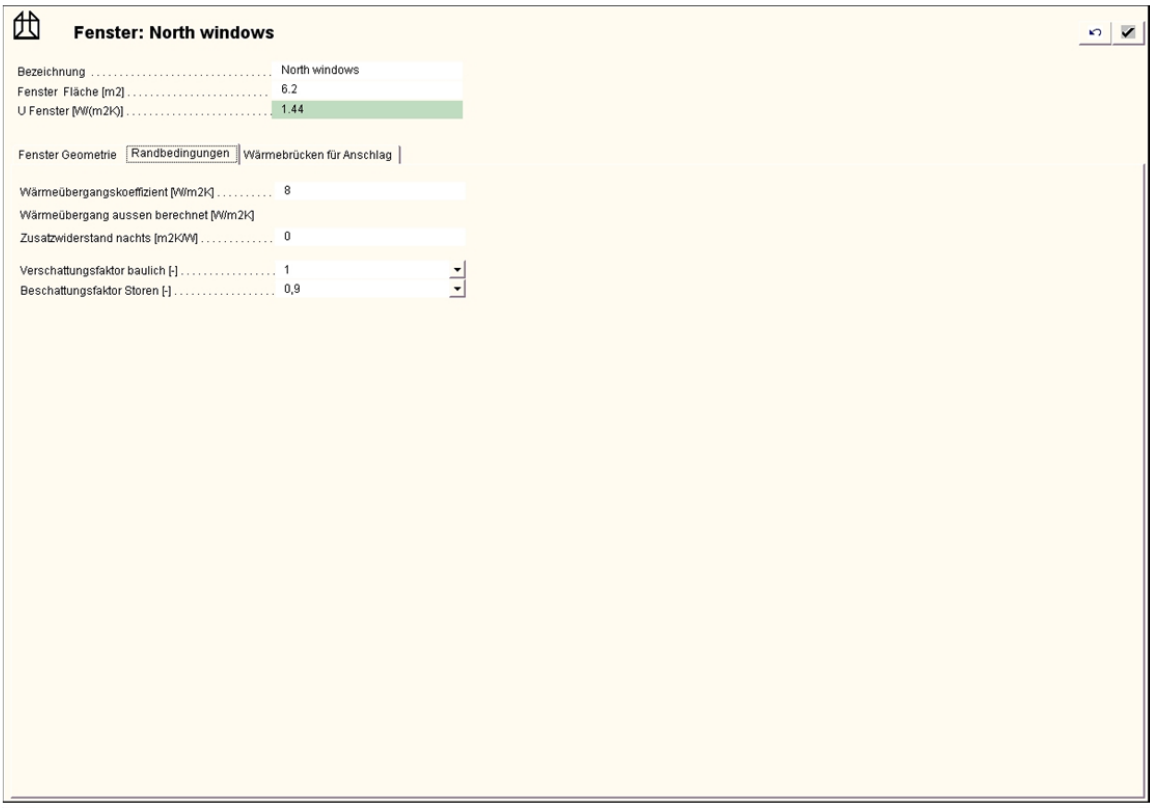
Wand: North facade

Bezeichnung	North facade
Flächentyp	Wandfäche gegen Aussenklim
Bauteil	Wall with cladding
Fläche brutto [m2]	52.76
Fläche netto [m2]	46.56
Azimut [GRAD]	-180
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



Fenster: North windows

Bezeichnung	North windows
Fenster Fläche [m2]	6.2
U Fenster [W/(m2K)]	1.44
Verglasung	2IG E03 (Ar)
Glas Fläche [m2]	4.51
Rahmen Profil	Holz
Rahmen U-wert [W/m2K]	1.4
Rahmen Fläche [m2]	1.69
Rahmenanteil [%]	27.26
Abstandhalter	Edelstahl
Kantenverlust [W/(mK)]	0.06
Perimeter [m]	26.08
Verlust Rahmen + Abstandhalter [W/K]	3.93
Total mit Wärmebrücken [W/K]	5.75

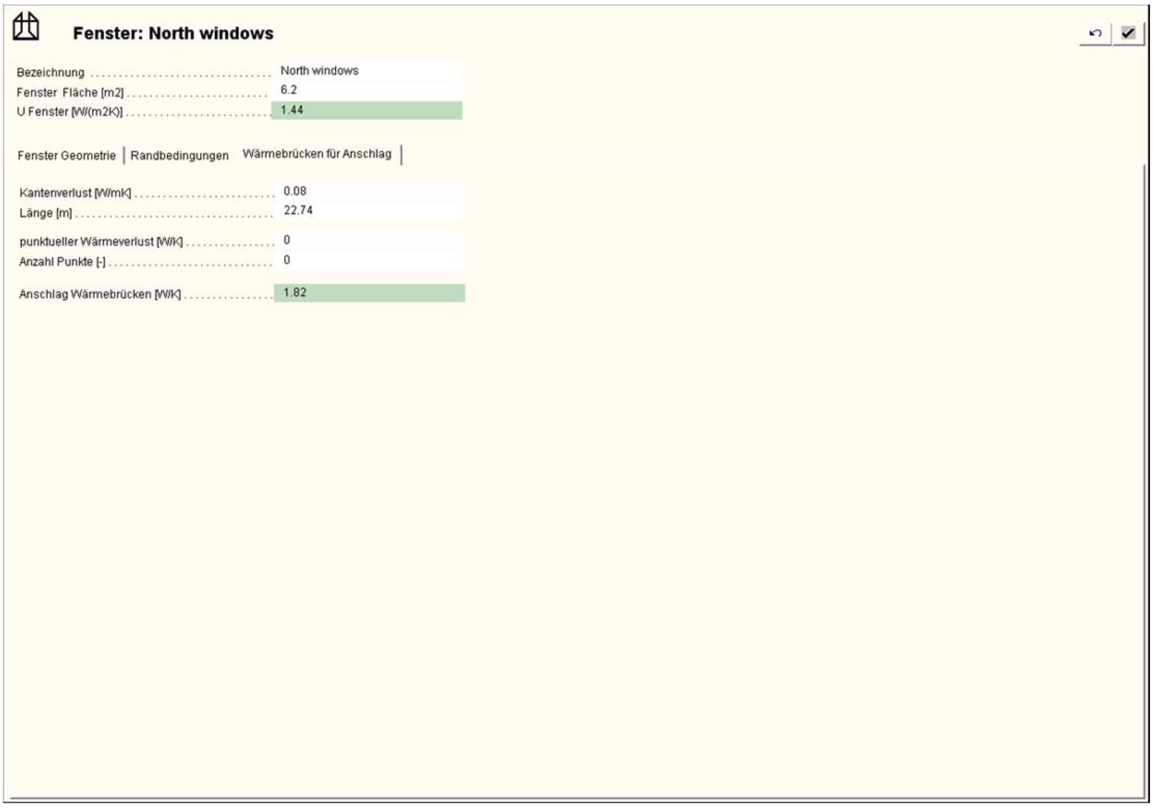


Fenster: North windows

Bezeichnung: North windows
Fenster Fläche [m2]: 6.2
U Fenster [W/(m2K)]: 1.44

Wärmeübergangskoeffizient [W/m2K]: 8
Wärmeübergang aussen berechnet [W/m2K]
Zusatzwiderstand nachts [m2K/W]: 0

Verschattungsfaktor baulich [-]: 1
Beschattungsfaktor Storen [-]: 0,9



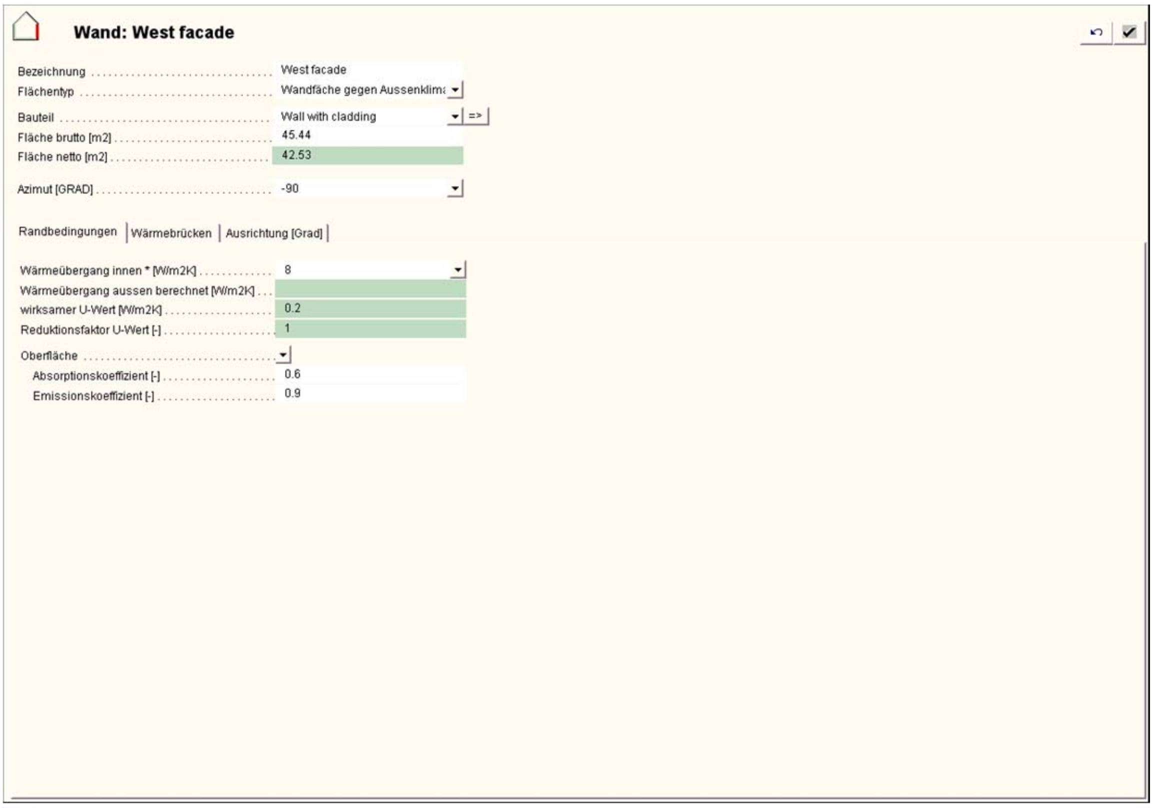
Fenster: North windows

Bezeichnung: North windows
Fenster Fläche [m2]: 6.2
U Fenster [W/(m2K)]: 1.44

Kantenverlust [W/mK]: 0.08
Länge [m]: 22.74

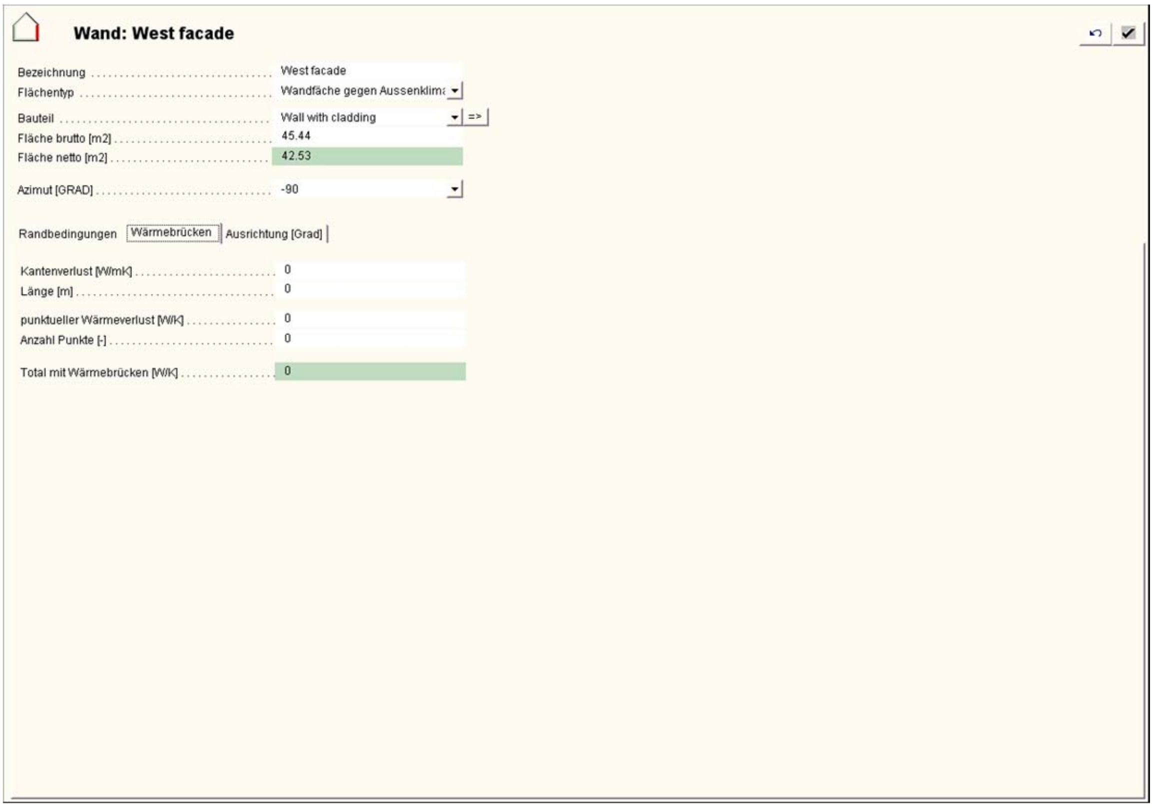
punktueller Wärmeverlust [W/K]: 0
Anzahl Punkte [-]: 0

Anschlag Wärmebrücken [W/K]: 1.82



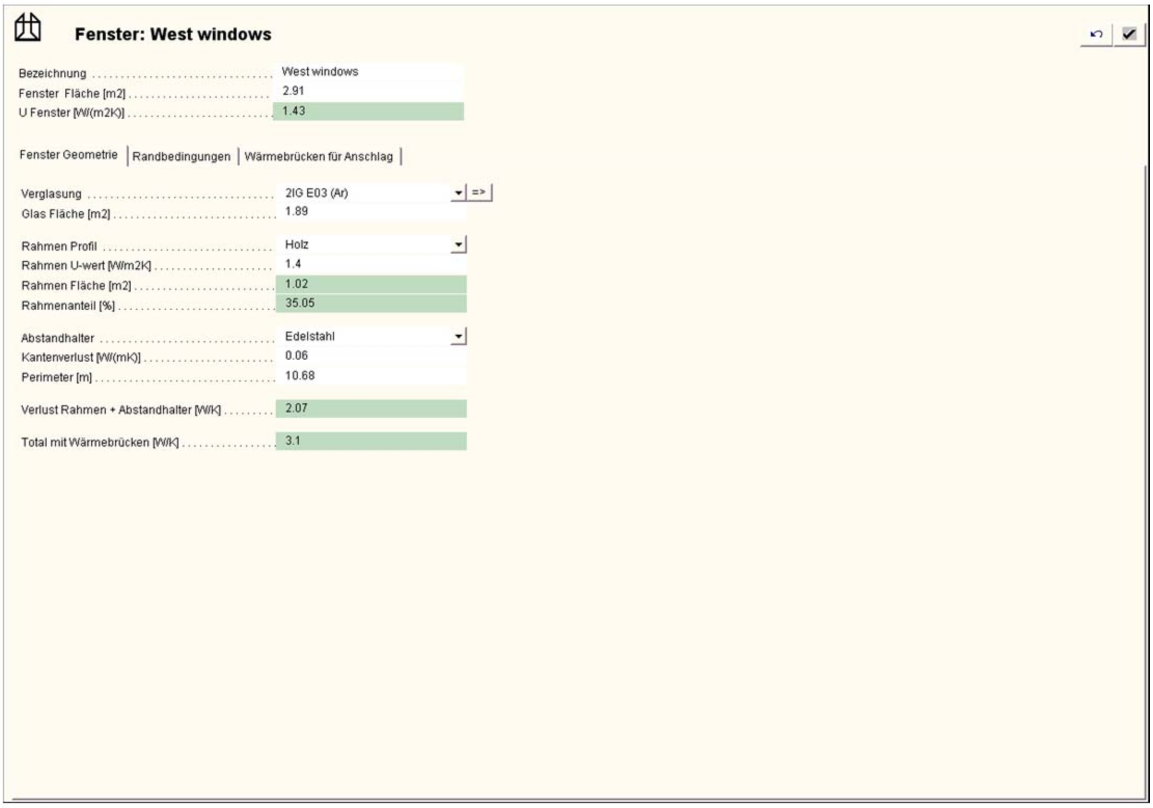
Wand: West facade

Bezeichnung	West facade
Flächentyp	Wandfäche gegen Aussenklim:
Bauteil	Wall with cladding
Fläche brutto [m2]	45.44
Fläche netto [m2]	42.53
Azimut [GRAD]	-90
Wärmeübergang innen * [W/m2K]	8
Wärmeübergang aussen berechnet [W/m2K]	
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	1
Oberfläche	
Absorptionskoeffizient [-]	0.6
Emissionskoeffizient [-]	0.9



Wand: West facade

Bezeichnung	West facade
Flächentyp	Wandfäche gegen Aussenklim:
Bauteil	Wall with cladding
Fläche brutto [m2]	45.44
Fläche netto [m2]	42.53
Azimut [GRAD]	-90
Kantenverlust [W/mK]	0
Länge [m]	0
punktueller Wärmeverlust [W/K]	0
Anzahl Punkte [-]	0
Total mit Wärmebrücken [W/K]	0



Fenster: West windows

Bezeichnung .... West windows
Fenster Fläche [m2] 2.91
U Fenster [W/(m2K)] 1.43

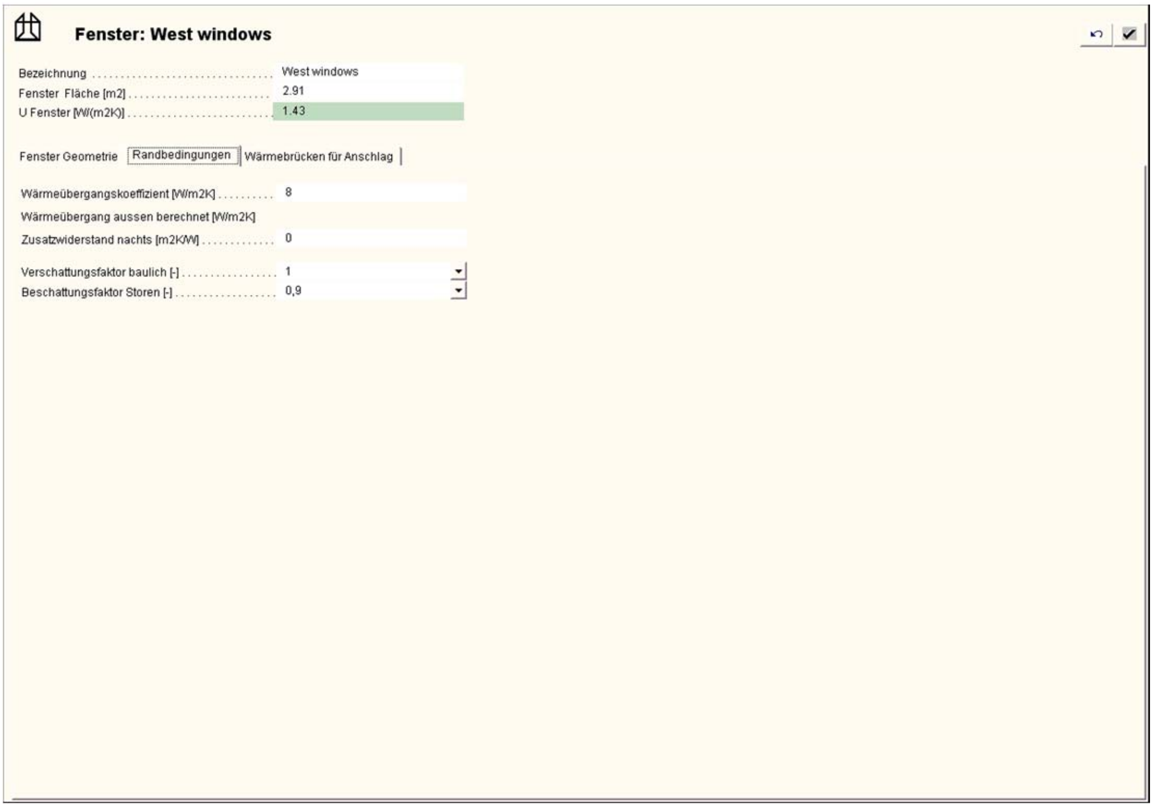
Verglasung .... 2IG E03 (Ar)
Glas Fläche [m2] 1.89

Rahmen Profil .... Holz
Rahmen U-wert [W/m2K] 1.4
Rahmen Fläche [m2] 1.02
Rahmenanteil [%] 35.05

Abstandhalter .... Edelstahl
Kantenverlust [W/(mK)] 0.06
Perimeter [m] 10.68

Verlust Rahmen + Abstandhalter [W/K] 2.07

Total mit Wärmebrücken [W/K] 3.1

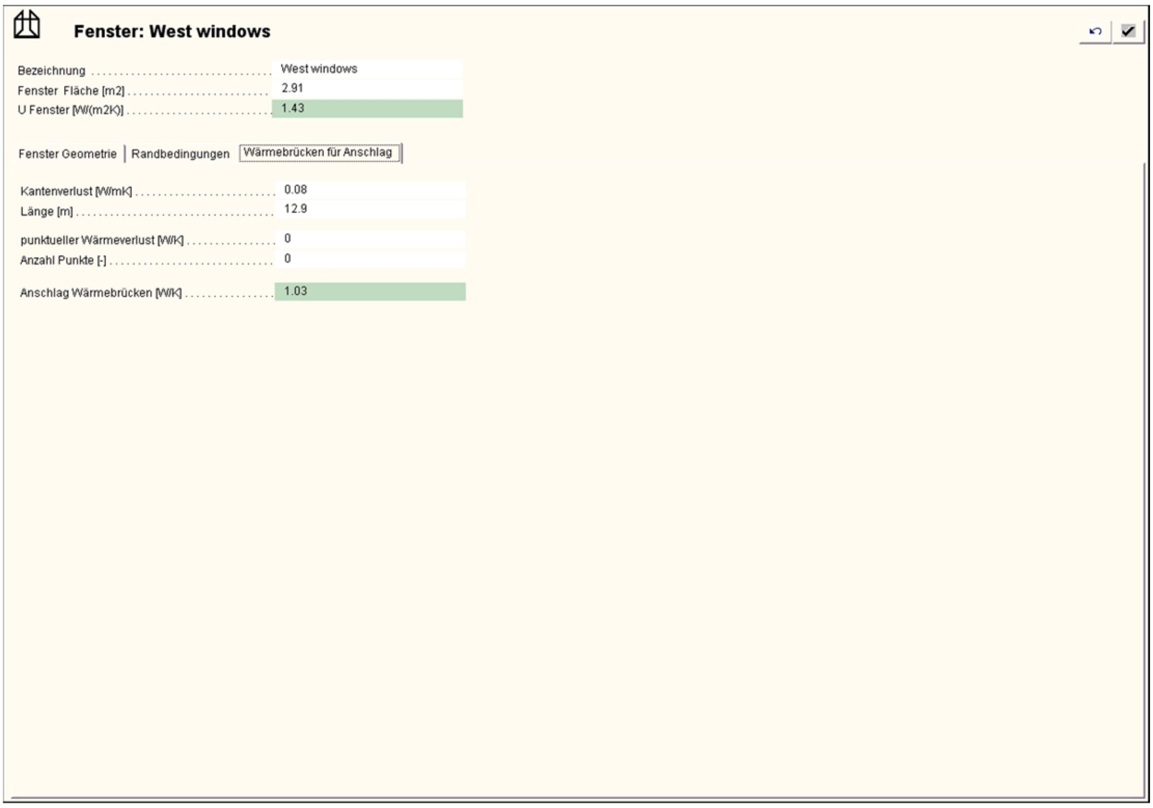


Fenster: West windows

Bezeichnung .... West windows
Fenster Fläche [m2] 2.91
U Fenster [W/(m2K)] 1.43

Wärmeübergangskoeffizient [W/m2K] 8
Wärmeübergang aussen berechnet [W/m2K]
Zusatzwiderstand nachts [m2K/W] 0

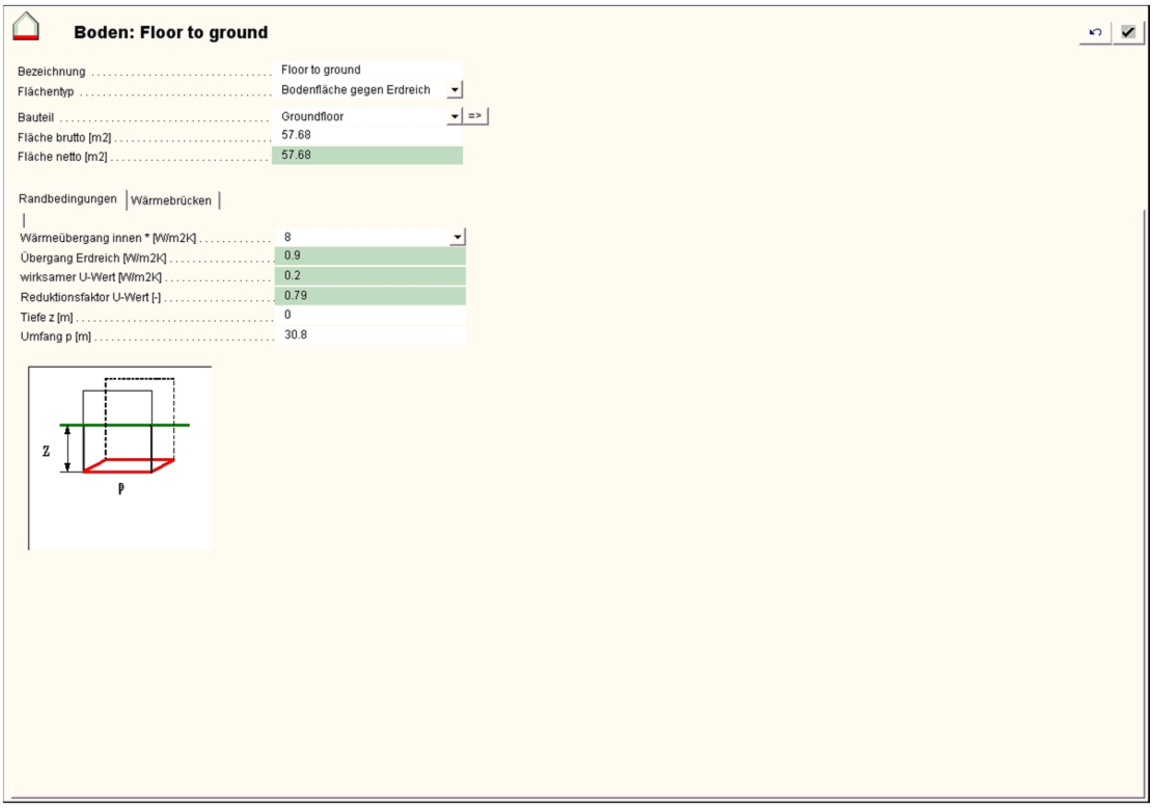
Verschattungsfaktor baulich [-] 1
Beschattungsfaktor Storen [-] 0,9



Fenster: West windows

Bezeichnung	West windows
Fenster Fläche [m2]	2.91
U Fenster [W/(m2K)]	1.43

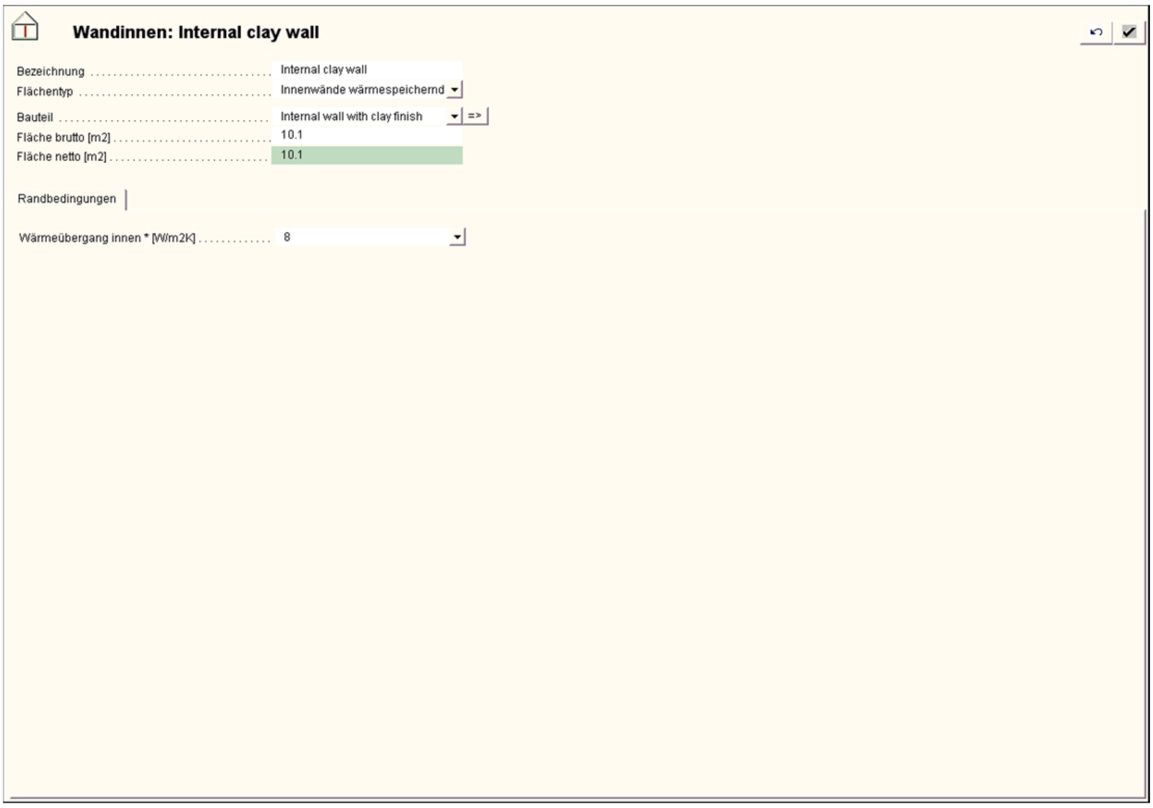
Kantenverlust [W/mK]	0.08
Länge [m]	12.9
punktueller Wärmeverlust [W/K]	0
Anzahl Punkte [-]	0
Anschlag Wärmebrücken [W/K]	1.03



Boden: Floor to ground

Bezeichnung	Floor to ground
Flächentyp	Bodenfläche gegen Erdreich
Bauteil	Groundfloor
Fläche brutto [m2]	57.68
Fläche netto [m2]	57.68

Wärmeübergang innen * [W/m2K]	8
Übergang Erdreich [W/m2K]	0.9
wirksamer U-Wert [W/m2K]	0.2
Reduktionsfaktor U-Wert [-]	0.79
Tiefe z [m]	0
Umfang p [m]	30.8

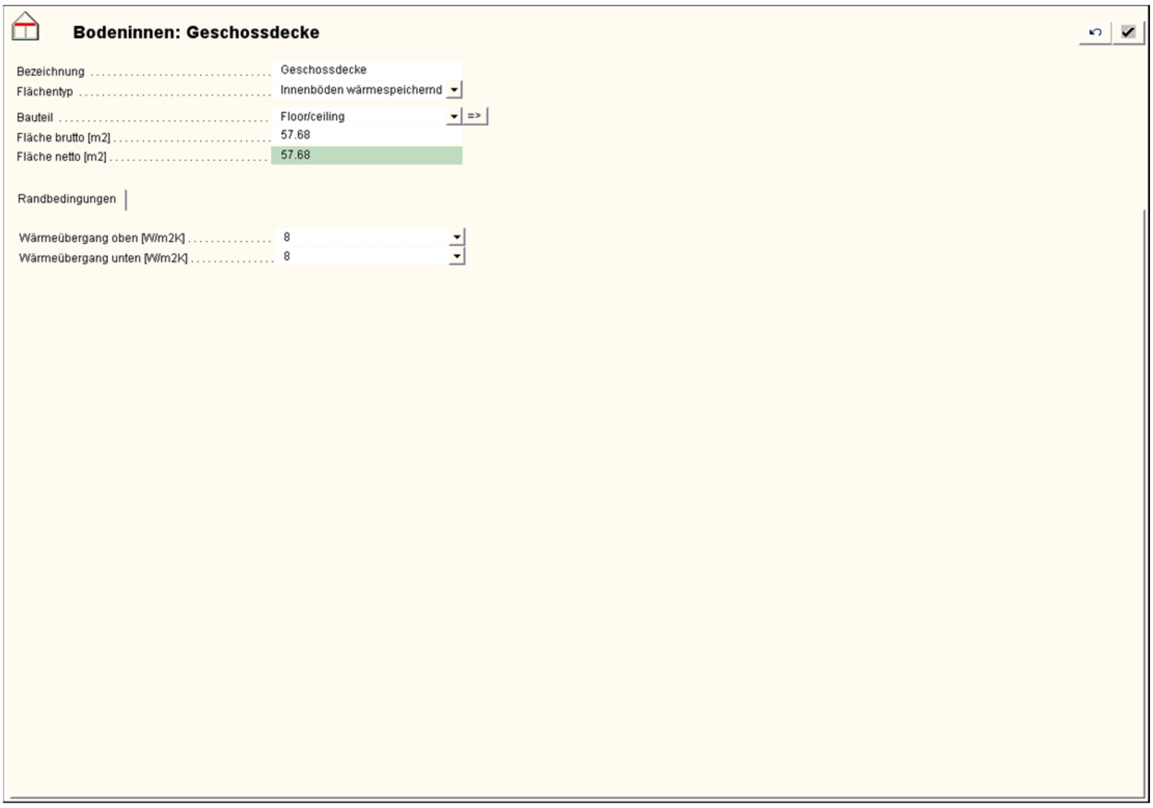


Wandinnen: Internal clay wall

Bezeichnung	Internal clay wall
Flächentyp	Innenwände wärmespeichernd
Bauteil	Internal wall with clay finish
Fläche brutto [m2]	10.1
Fläche netto [m2]	10.1

Randbedingungen

Wärmeübergang innen * [W/m2K]	8

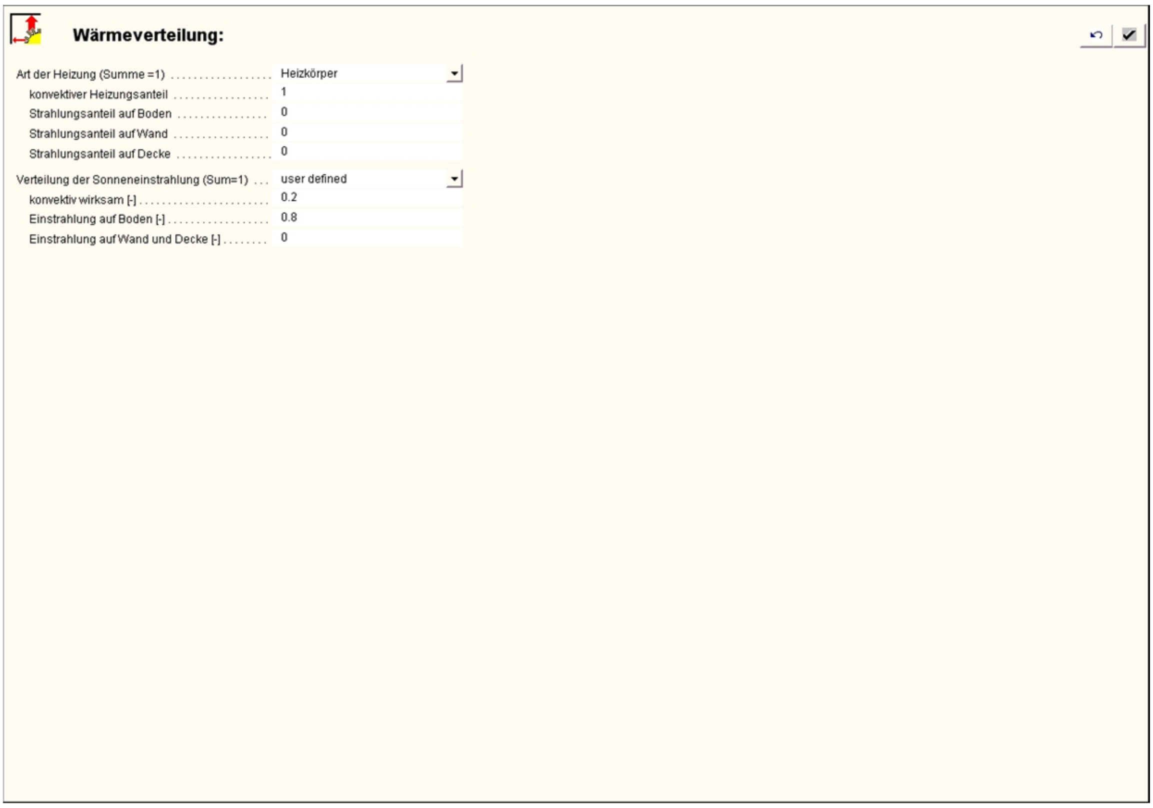


Bodeninnen: Geschossdecke

Bezeichnung	Geschossdecke
Flächentyp	Innenböden wärmespeichernd
Bauteil	Floor/ceiling
Fläche brutto [m2]	57.68
Fläche netto [m2]	57.68

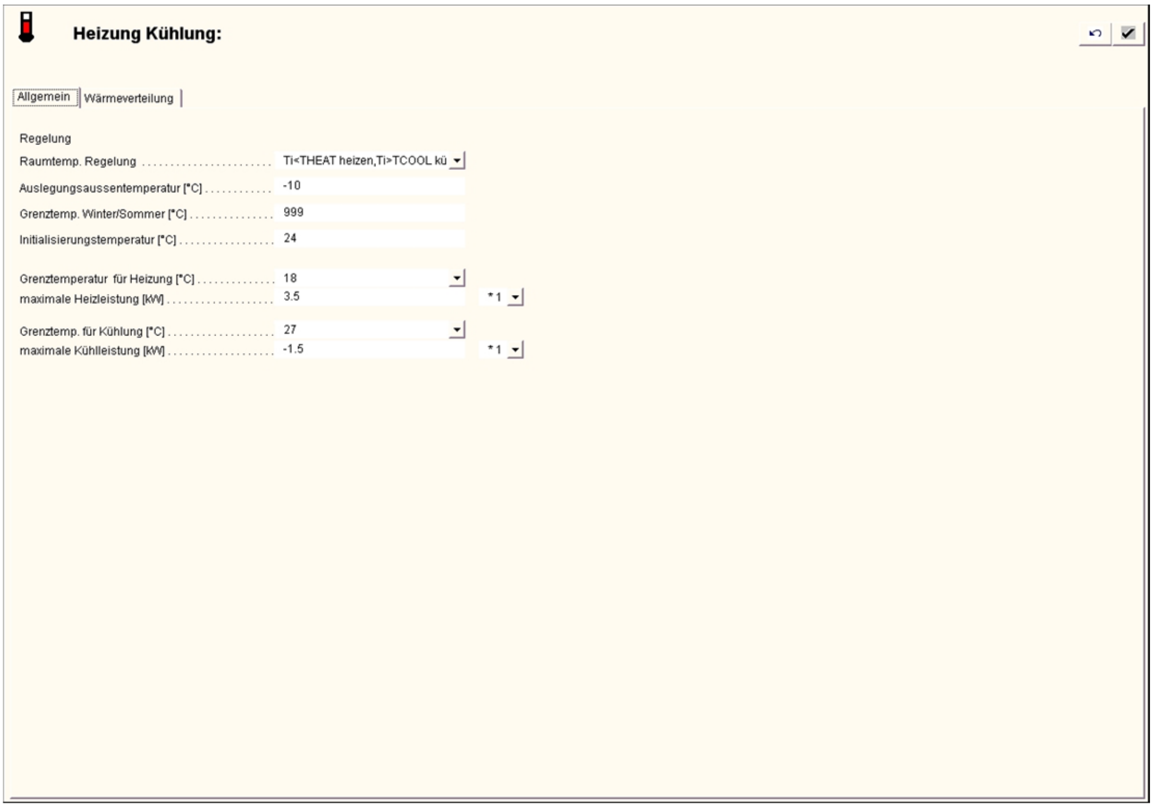
Randbedingungen

Wärmeübergang oben [W/m2K]	8
Wärmeübergang unten [W/m2K]	8



Wärmeverteilung:

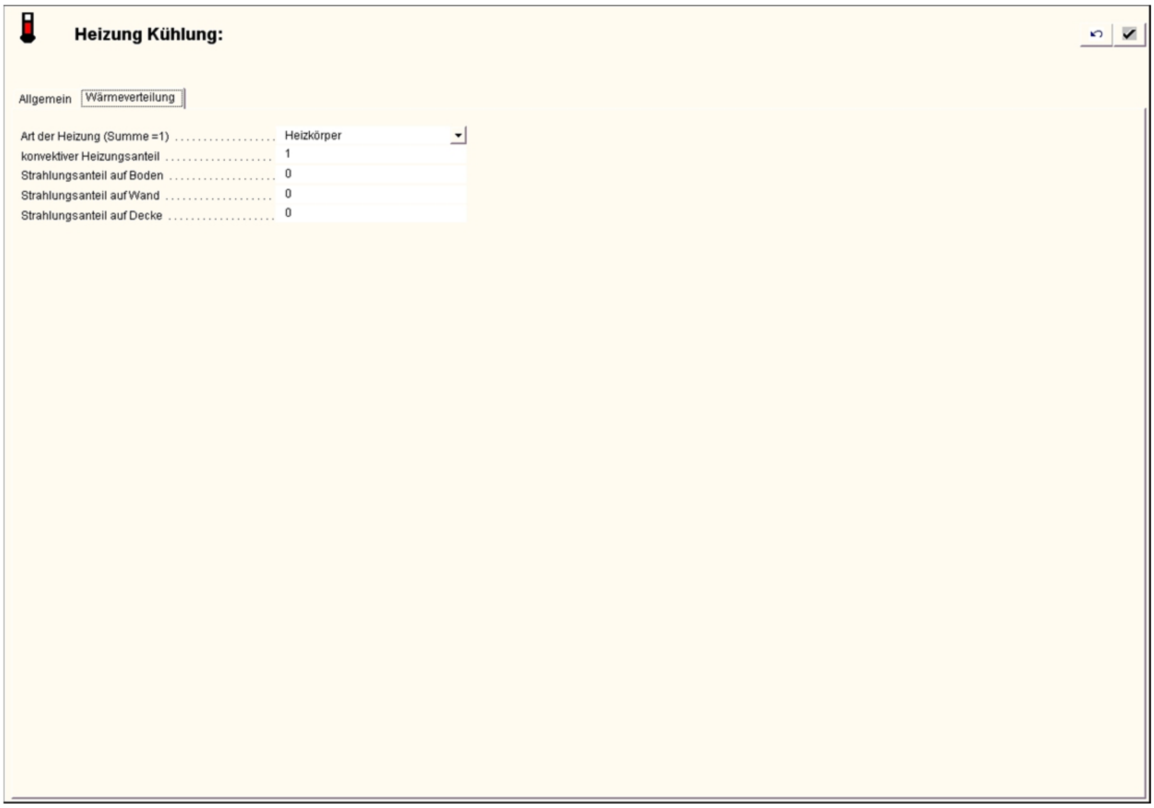
Art der Heizung (Summe =1)	Heizkörper
konvektiver Heizungsanteil	1
Strahlungsanteil auf Boden	0
Strahlungsanteil auf Wand	0
Strahlungsanteil auf Decke	0
Verteilung der Sonneneinstrahlung (Sum=1)	user defined
konvektiv wirksam [-]	0.2
Einstrahlung auf Boden [-]	0.8
Einstrahlung auf Wand und Decke [-]	0



Heizung Kühlung:

Regelung

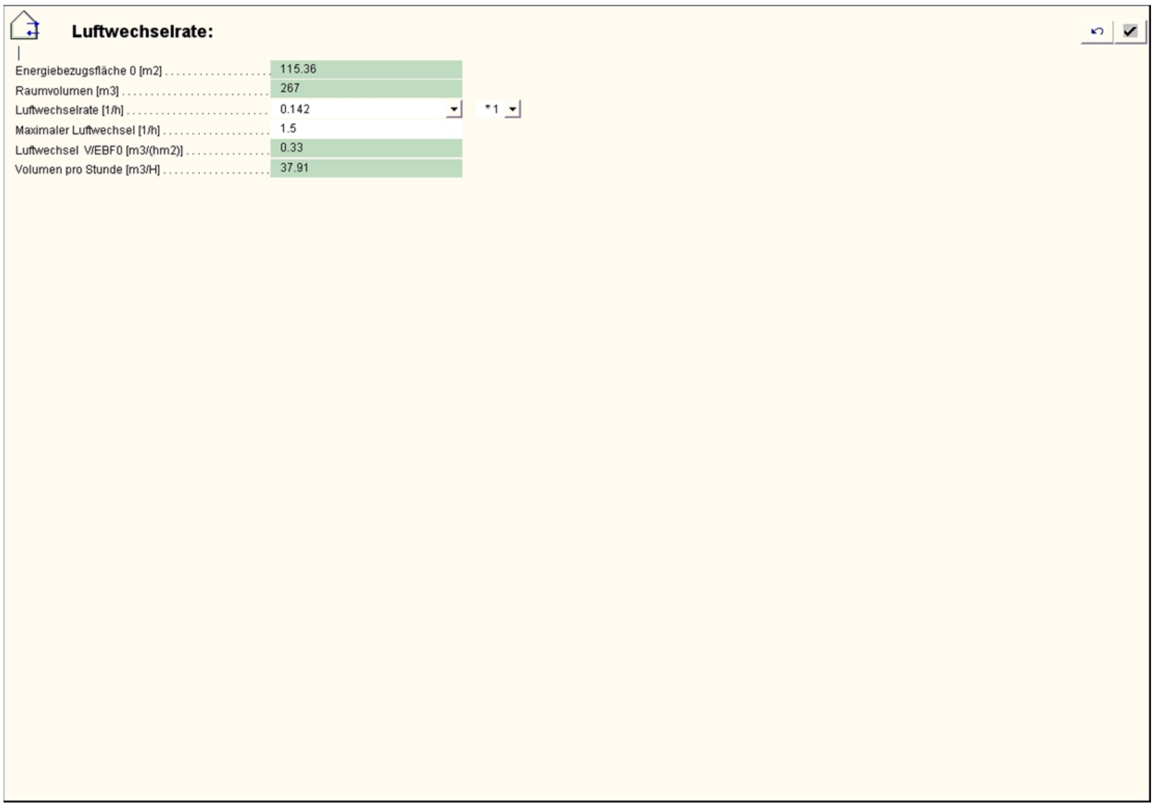
Raumtemp. Regelung	Ti<THEAT heizen,Ti>TCOOL kü	
Auslegungsaussentemperatur [°C]	-10	
Grenztemp. Winter/Sommer [°C]	999	
Initialisierungstemperatur [°C]	24	
Grenztemperatur für Heizung [°C]	18	
maximale Heizleistung [kW]	3.5	*1
Grenztemp. für Kühlung [°C]	27	
maximale Kühlleistung [kW]	-1.5	*1



Heizung Kühlung:

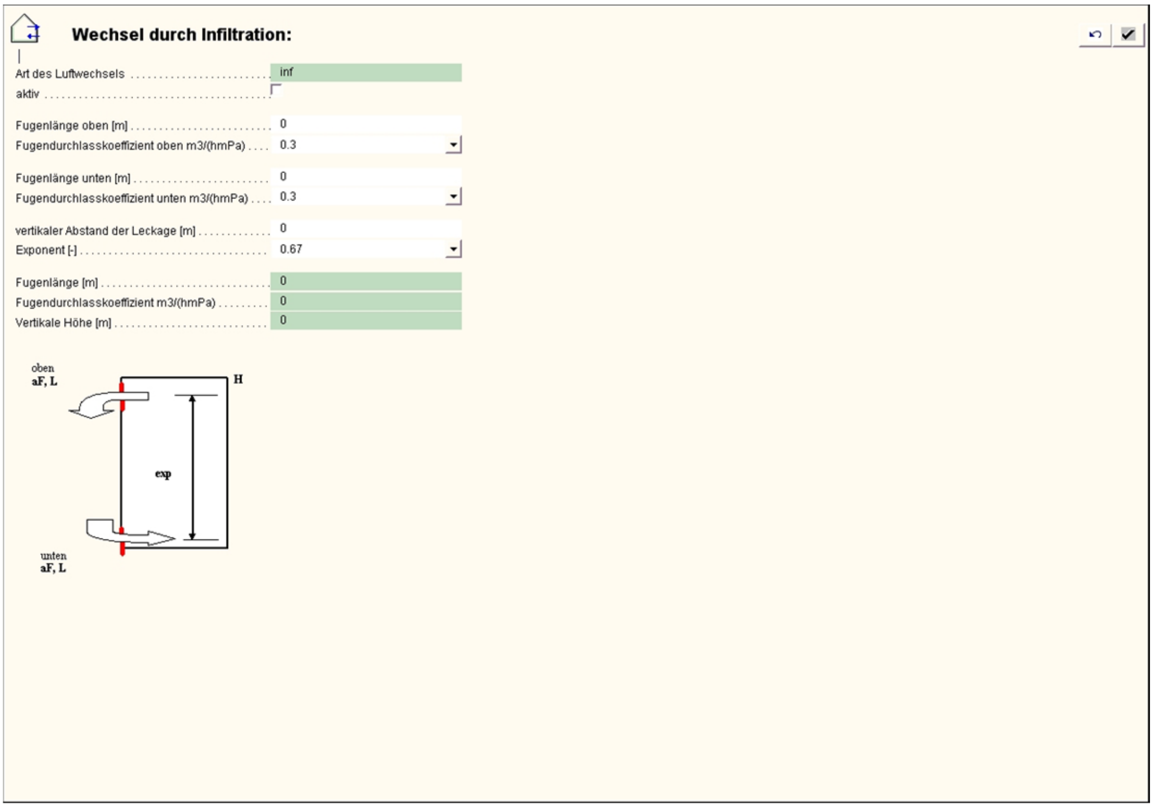
Allgemein | Wärmeverteilung

Art der Heizung (Summe =1)	Heizkörper
konvektiver Heizungsanteil	1
Strahlungsanteil auf Boden	0
Strahlungsanteil auf Wand	0
Strahlungsanteil auf Decke	0



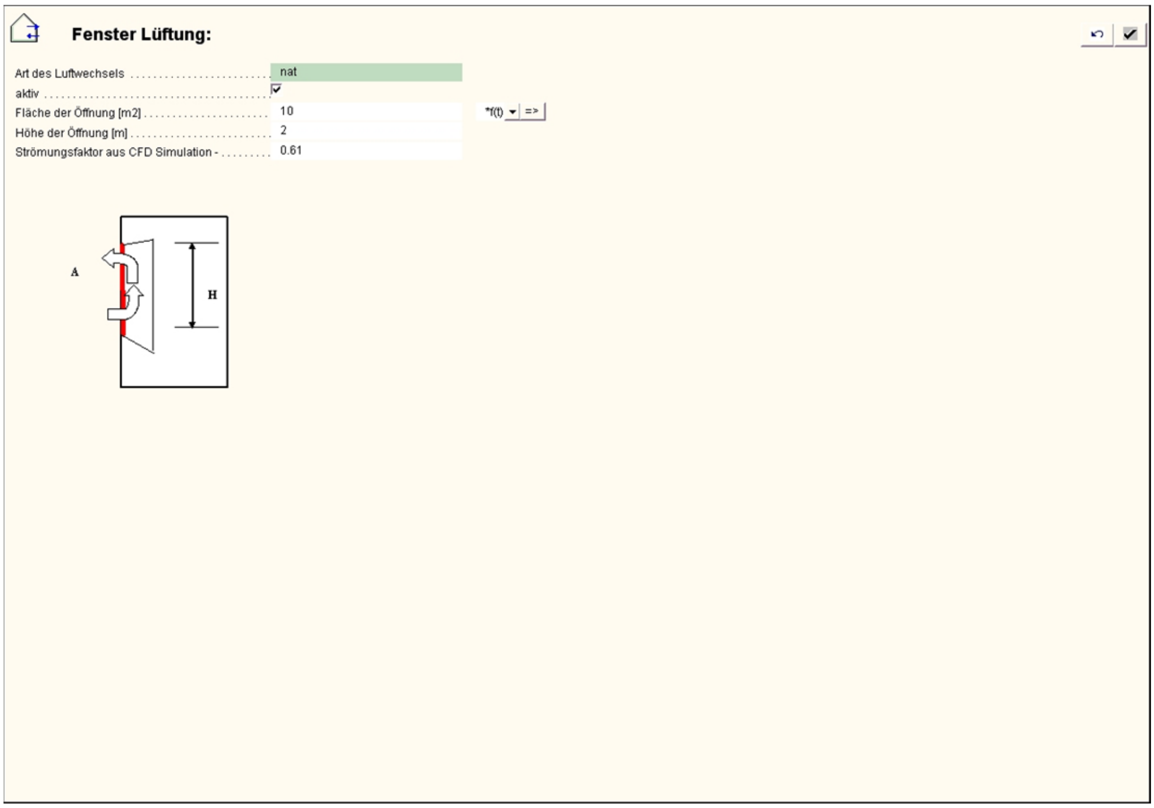
Luftwechselrate:

Energiebezugsfläche 0 [m2]	115.36	
Raumvolumen [m3]	267	
Luftwechselrate [1/h]	0.142	*1
Maximaler Luftwechsel [1/h]	1.5	
Luftwechsel V/EBF0 [m3/(hm2)]	0.33	
Volumen pro Stunde [m3/H]	37.91	



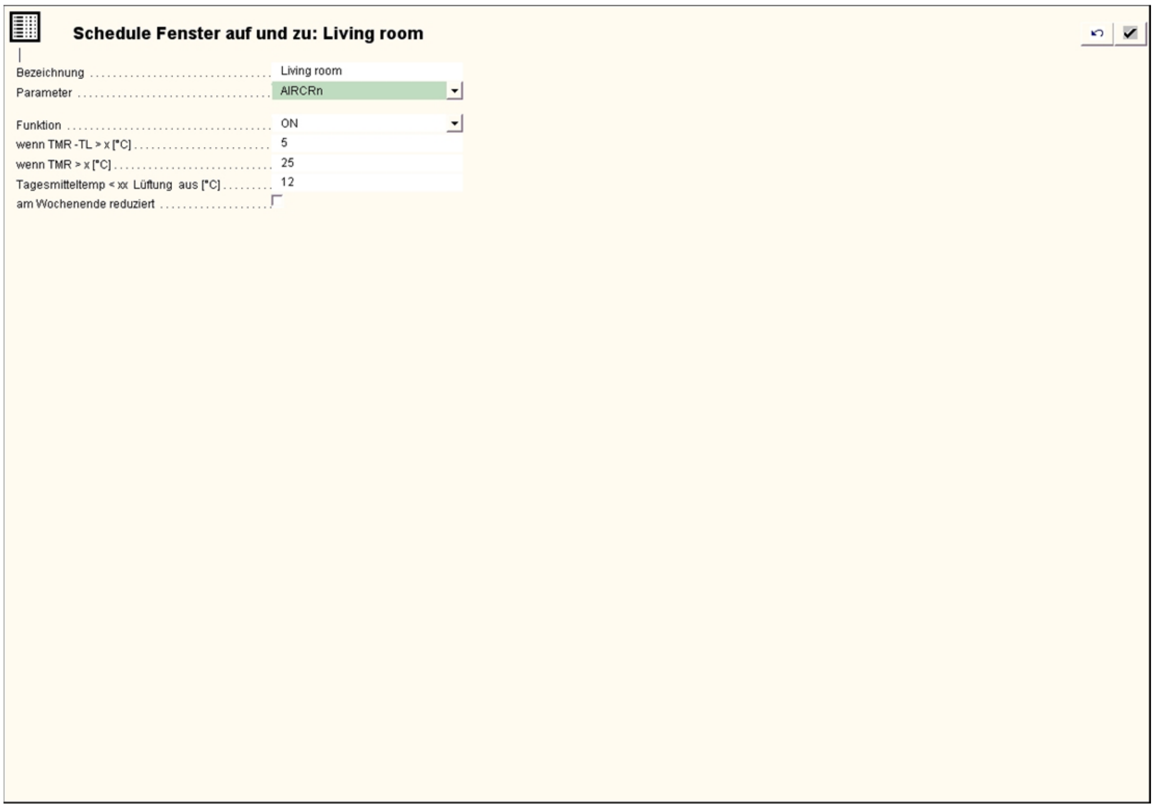
Wechsel durch Infiltration:

Art des Luftwechsels	inf
aktiv	☐
Fugenlänge oben [m]	0
Fugendurchlasskoeffizient oben m3/(hmPa)	0.3
Fugenlänge unten [m]	0
Fugendurchlasskoeffizient unten m3/(hmPa)	0.3
vertikaler Abstand der Leckage [m]	0
Exponent [-]	0.67
Fugenlänge [m]	0
Fugendurchlasskoeffizient m3/(hmPa)	0
Vertikale Höhe [m]	0



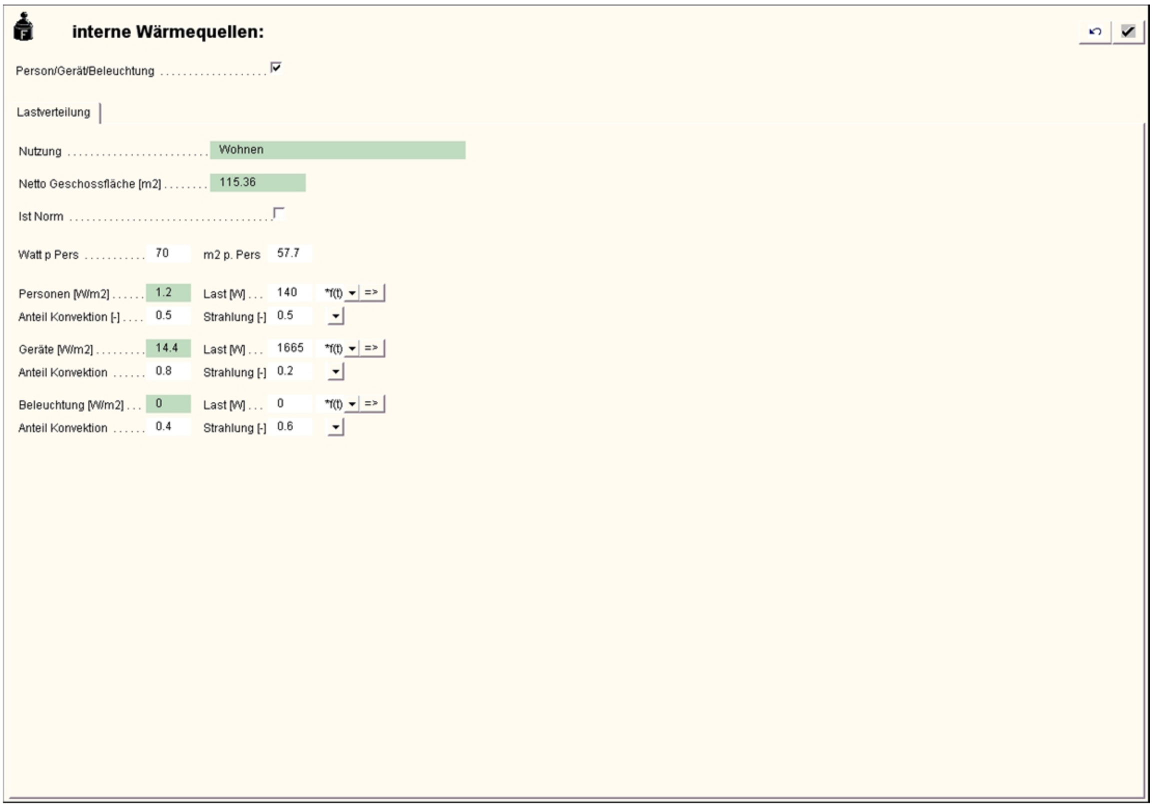
Fenster Lüftung:

Art des Luftwechsels	nat
aktiv	☑
Fläche der Öffnung [m2]	10
Höhe der Öffnung [m]	2
Strömungsfaktor aus CFD Simulation -	0.61



Schedule Fenster auf und zu: Living room

Bezeichnung: Living room
Parameter: AIRCRn
Funktion: ON
wenn TMR -TL > x [°C]: 5
wenn TMR > x [°C]: 25
Tagesmitteltemp < xx Lüftung aus [°C]: 12
am Wochenende reduziert: ☐



interne Wärmequellen:

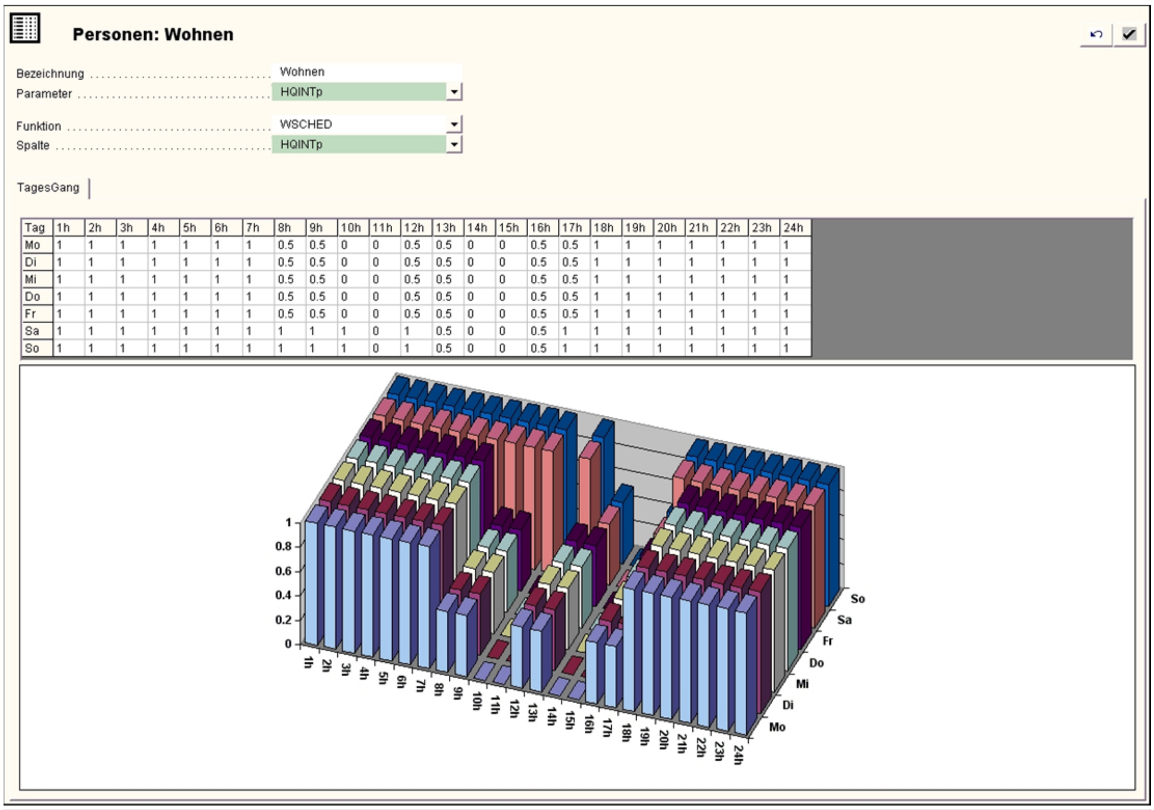
Person/Gerät/Beleuchtung: ☑

Lastverteilung

Nutzung: Wohnen
Netto Geschossfläche [m2]: 115.36
Ist Norm: ☐

Watt p Pers: 70 | m2 p. Pers: 57.7

Personen [W/m2]	1.2	Last [W]	140	*f(t)
Anteil Konvektion [-]	0.5	Strahlung [-]	0.5	
Geräte [W/m2]	14.4	Last [W]	1665	*f(t)
Anteil Konvektion	0.8	Strahlung [-]	0.2	
Beleuchtung [W/m2]	0	Last [W]	0	*f(t)
Anteil Konvektion	0.4	Strahlung [-]	0.6	



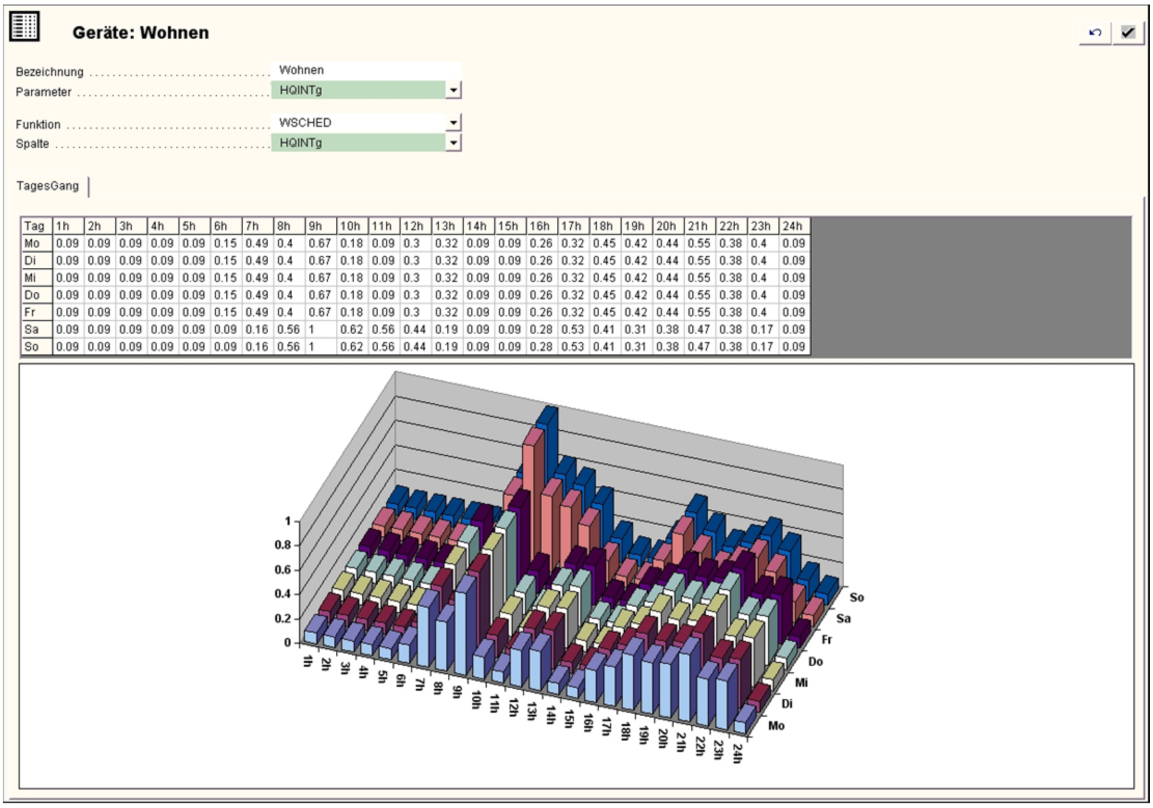
Personen: Wohnen

Bezeichnung .... Wohnen
Parameter .... HQINTp

Funktion .... WSCHED
Spalte .... HQINTp

TagesGang

Tag	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	24h
Mo	1	1	1	1	1	1	1	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	1	1	1	1	1	1	1
Di	1	1	1	1	1	1	1	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	1	1	1	1	1	1	1
Mi	1	1	1	1	1	1	1	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	1	1	1	1	1	1	1
Do	1	1	1	1	1	1	1	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	1	1	1	1	1	1	1
Fr	1	1	1	1	1	1	1	0.5	0.5	0	0	0.5	0.5	0	0	0.5	0.5	1	1	1	1	1	1	1
Sa	1	1	1	1	1	1	1	1	1	1	0	1	0.5	0	0	0.5	1	1	1	1	1	1	1	1
So	1	1	1	1	1	1	1	1	1	1	0	1	0.5	0	0	0.5	1	1	1	1	1	1	1	1



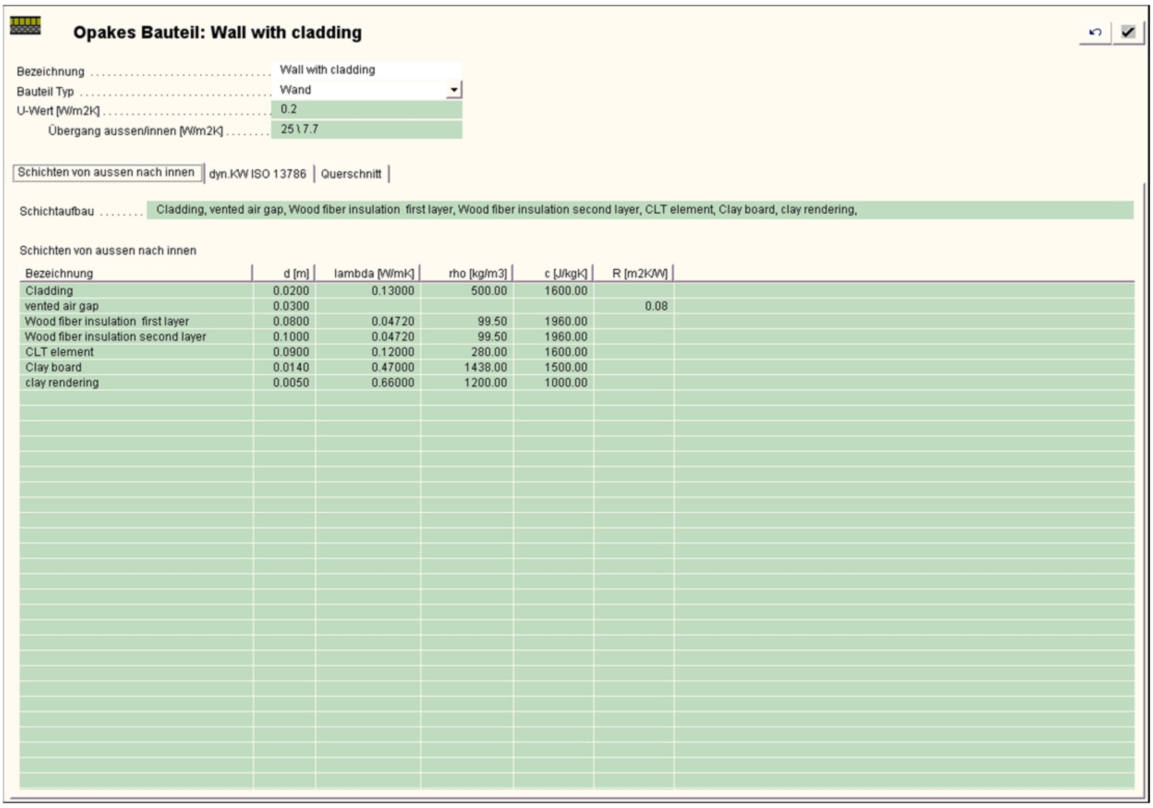
Geräte: Wohnen

Bezeichnung .... Wohnen
Parameter .... HQINTg

Funktion .... WSCHED
Spalte .... HQINTg

TagesGang

Tag	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	24h
Mo	0.09	0.09	0.09	0.09	0.09	0.15	0.49	0.4	0.67	0.18	0.09	0.3	0.32	0.09	0.09	0.26	0.32	0.45	0.42	0.44	0.55	0.38	0.4	0.09
Di	0.09	0.09	0.09	0.09	0.09	0.15	0.49	0.4	0.67	0.18	0.09	0.3	0.32	0.09	0.09	0.26	0.32	0.45	0.42	0.44	0.55	0.38	0.4	0.09
Mi	0.09	0.09	0.09	0.09	0.09	0.15	0.49	0.4	0.67	0.18	0.09	0.3	0.32	0.09	0.09	0.26	0.32	0.45	0.42	0.44	0.55	0.38	0.4	0.09
Do	0.09	0.09	0.09	0.09	0.09	0.15	0.49	0.4	0.67	0.18	0.09	0.3	0.32	0.09	0.09	0.26	0.32	0.45	0.42	0.44	0.55	0.38	0.4	0.09
Fr	0.09	0.09	0.09	0.09	0.09	0.15	0.49	0.4	0.67	0.18	0.09	0.3	0.32	0.09	0.09	0.26	0.32	0.45	0.42	0.44	0.55	0.38	0.4	0.09
Sa	0.09	0.09	0.09	0.09	0.09	0.09	0.16	0.56	1	0.62	0.56	0.44	0.19	0.09	0.09	0.28	0.53	0.41	0.31	0.38	0.47	0.38	0.17	0.09
So	0.09	0.09	0.09	0.09	0.09	0.09	0.16	0.56	1	0.62	0.56	0.44	0.19	0.09	0.09	0.28	0.53	0.41	0.31	0.38	0.47	0.38	0.17	0.09



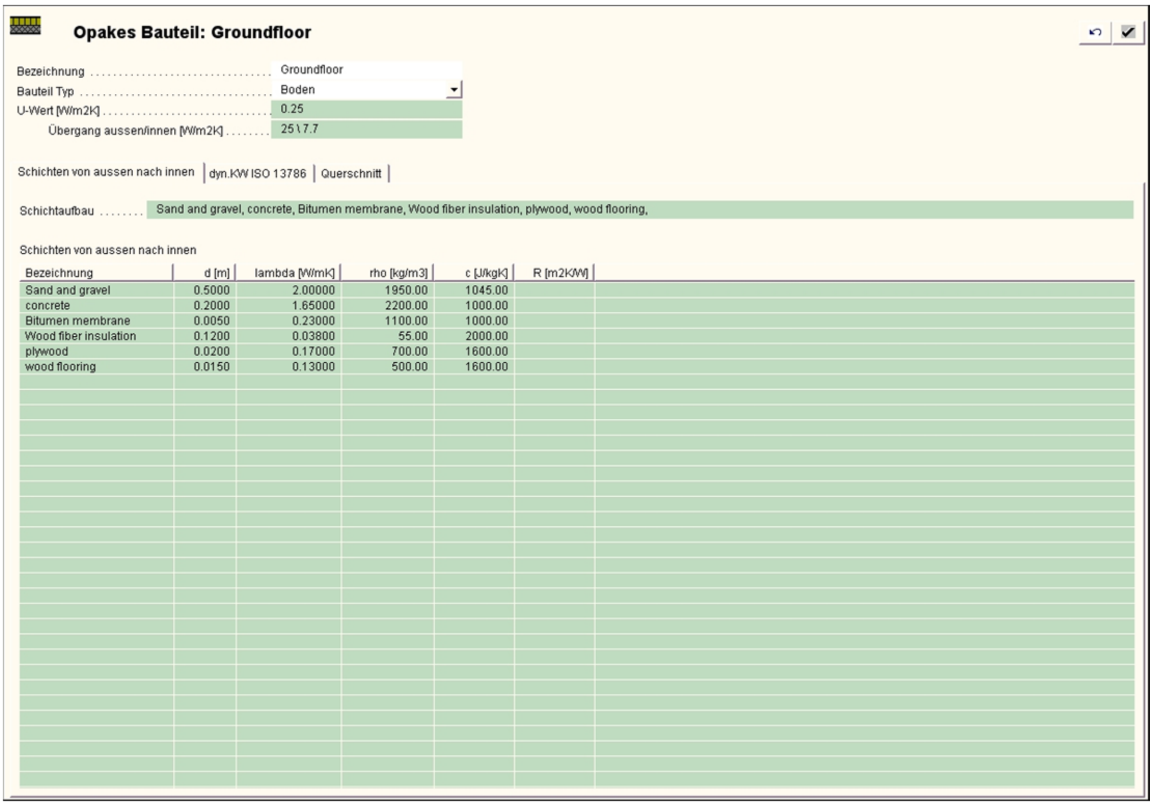
Opakes Bauteil: Wall with cladding

Bezeichnung	Wall with cladding
Bauteil Typ	Wand
U-Wert [W/m2K]	0.2
Übergang aussen/innen [W/m2K]	25 \ 7.7

Schichtaufbau .... Cladding, vented air gap, Wood fiber insulation first layer, Wood fiber insulation second layer, CLT element, Clay board, clay rendering,

Schichten von aussen nach innen

Bezeichnung	d [m]	lambda [W/mK]	rho [kg/m3]	c [J/kgK]	R [m2K/W]
Cladding	0.0200	0.13000	500.00	1600.00	
vented air gap	0.0300				0.08
Wood fiber insulation first layer	0.0800	0.04720	99.50	1960.00	
Wood fiber insulation second layer	0.1000	0.04720	99.50	1960.00	
CLT element	0.0900	0.12000	280.00	1600.00	
Clay board	0.0140	0.47000	1438.00	1500.00	
clay rendering	0.0050	0.66000	1200.00	1000.00	



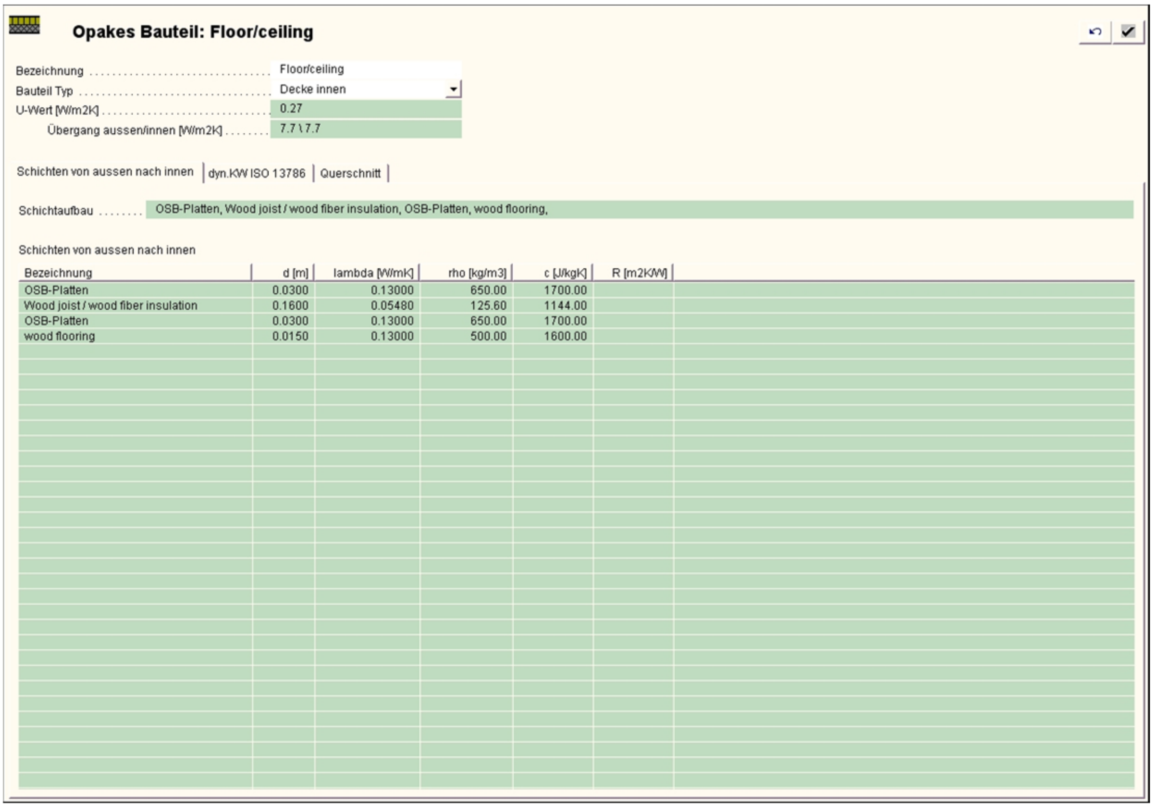
Opakes Bauteil: Groundfloor

Bezeichnung	Groundfloor
Bauteil Typ	Boden
U-Wert [W/m2K]	0.25
Übergang aussen/innen [W/m2K]	25 \ 7.7

Schichtaufbau .... Sand and gravel, concrete, Bitumen membrane, Wood fiber insulation, plywood, wood flooring,

Schichten von aussen nach innen

Bezeichnung	d [m]	lambda [W/mK]	rho [kg/m3]	c [J/kgK]	R [m2K/W]
Sand and gravel	0.5000	2.00000	1950.00	1045.00	
concrete	0.2000	1.65000	2200.00	1000.00	
Bitumen membrane	0.0050	0.23000	1100.00	1000.00	
Wood fiber insulation	0.1200	0.03800	55.00	2000.00	
plywood	0.0200	0.17000	700.00	1600.00	
wood flooring	0.0150	0.13000	500.00	1600.00	



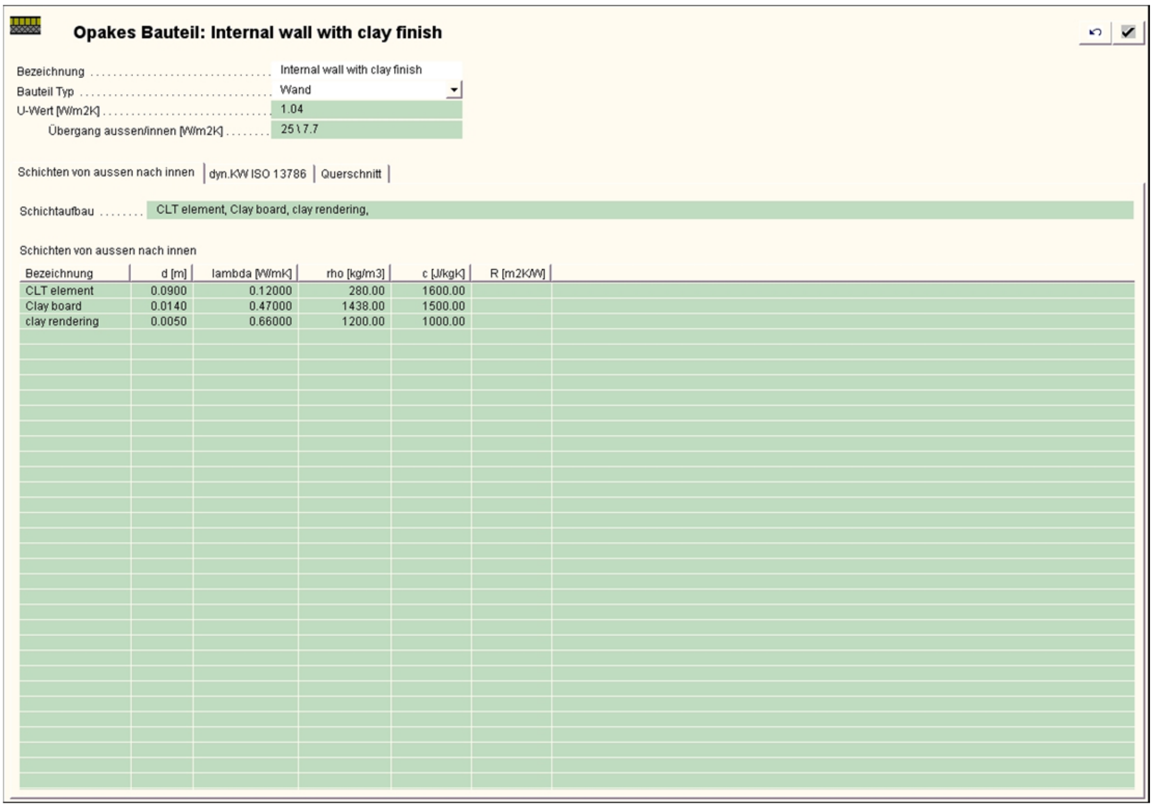
Opakes Bauteil: Floor/ceiling

Bezeichnung .... Floor/ceiling
Bauteil Typ .... Decke innen
U-Wert [W/m2K] 0.27
Übergang aussen/innen [W/m2K] .... 7.7 \ 7.7

Schichtaufbau .... OSB-Platten, Wood joist / wood fiber insulation, OSB-Platten, wood flooring,

Schichten von aussen nach innen

Bezeichnung	d [m]	lambda [W/mK]	rho [kg/m3]	c [J/kgK]	R [m2K/W]
OSB-Platten	0.0300	0.13000	650.00	1700.00	
Wood joist / wood fiber insulation	0.1600	0.05480	125.60	1144.00	
OSB-Platten	0.0300	0.13000	650.00	1700.00	
wood flooring	0.0150	0.13000	500.00	1600.00	



Opakes Bauteil: Internal wall with clay finish

Bezeichnung .... Internal wall with clay finish
Bauteil Typ .... Wand
U-Wert [W/m2K] 1.04
Übergang aussen/innen [W/m2K] .... 25 \ 7.7

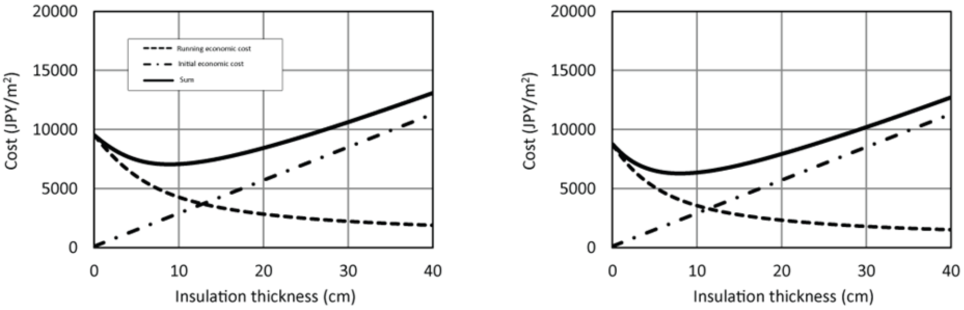
Schichtaufbau .... CLT element, Clay board, clay rendering,

Schichten von aussen nach innen

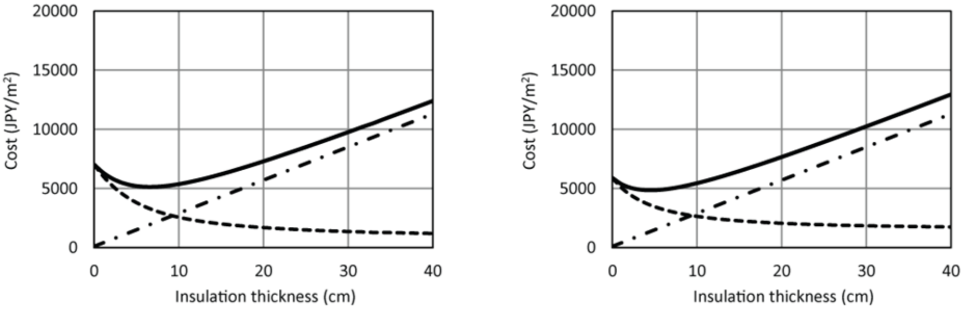
Bezeichnung	d [m]	lambda [W/mK]	rho [kg/m3]	c [J/kgK]	R [m2K/W]
CLT element	0.0900	0.12000	280.00	1600.00	
Clay board	0.0140	0.47000	1438.00	1500.00	
clay rendering	0.0050	0.66000	1200.00	1000.00	

Appendix C - Supplemental results for Chapter 5

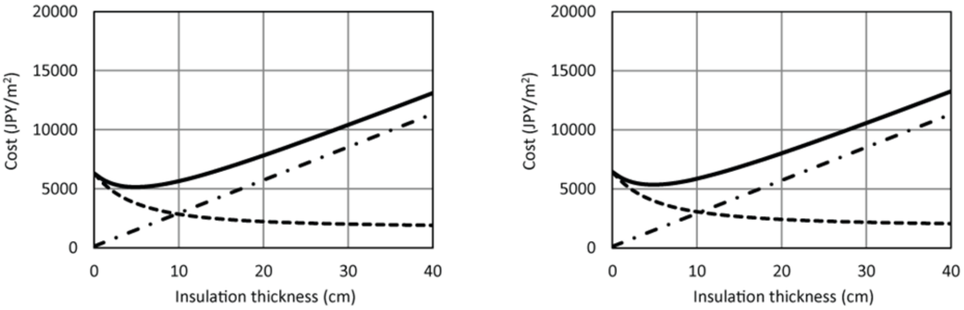
The results of economic analyses for the 8 investigated cities are shown in Figure C-1 (see 5.3.2.3).



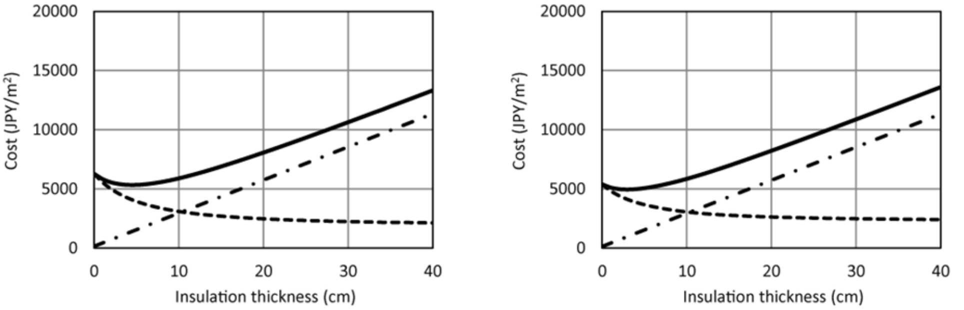
(a) Sapporo (b) Morioka



(c) Sendai (d) Tokyo



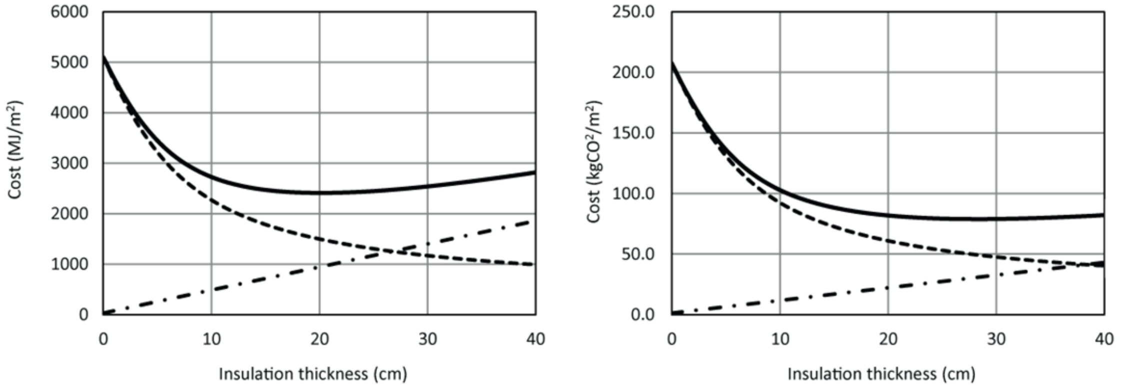
(e) Nagoya (f) Hiroshima



(g) Fukuoka (h) Kagoshima

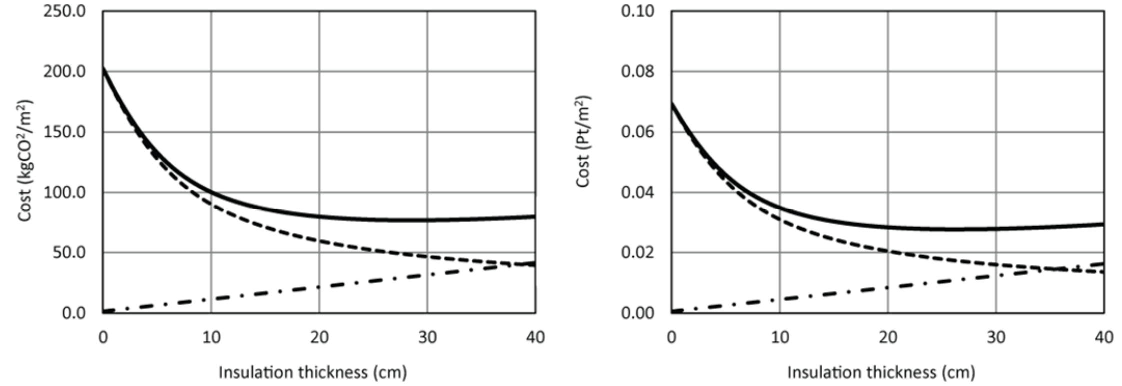
Figure C-1: Economic analyses for the 8 investigated cities

The results of ecological analyses for Sapporo, Morioka, Sendai, Tokyo, Hiroshima, Fukuoka and Kagoshima are shown in Figure C-2 – C-8 respectively (see 5.3.3.3).



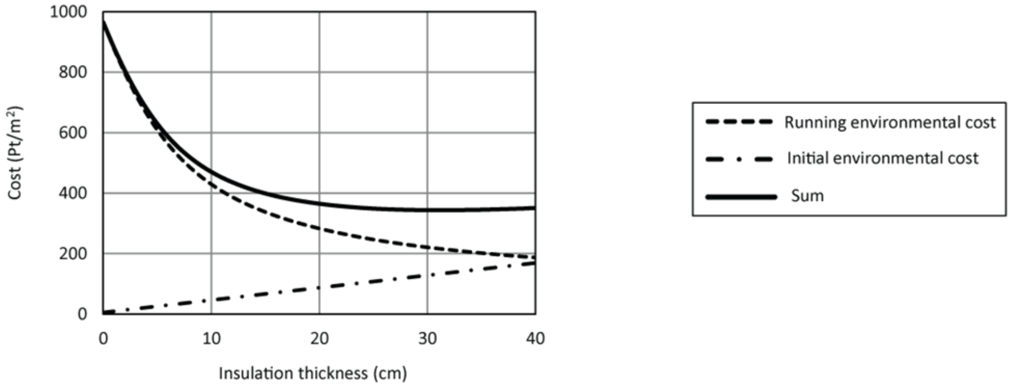
(a) CED

(b) IPCC 100



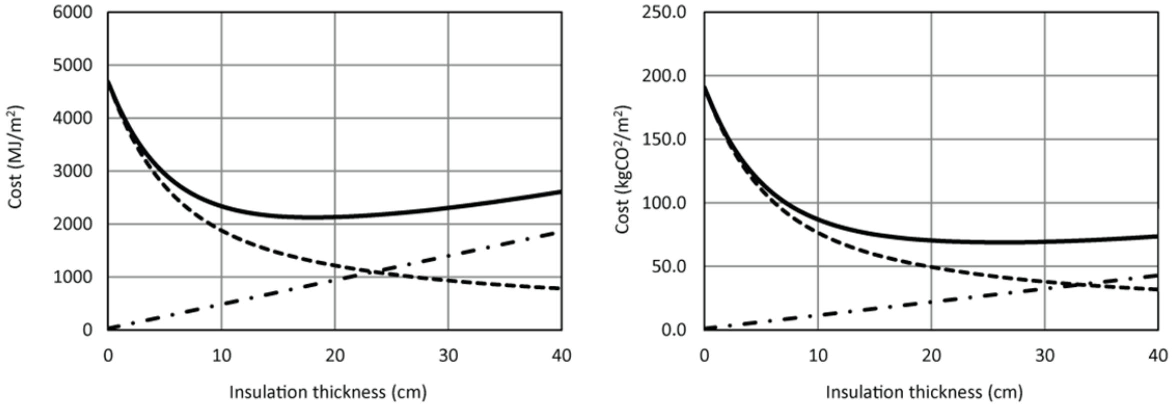
(c) IPCC 500

(d) Impact 2002+



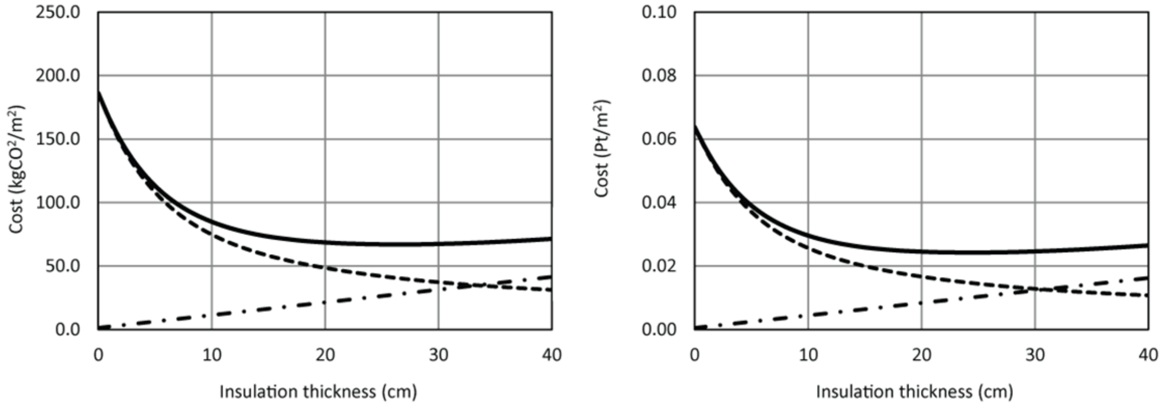
(e) Ecological footprint

Figure C-2: Ecological analyses for Sapporo



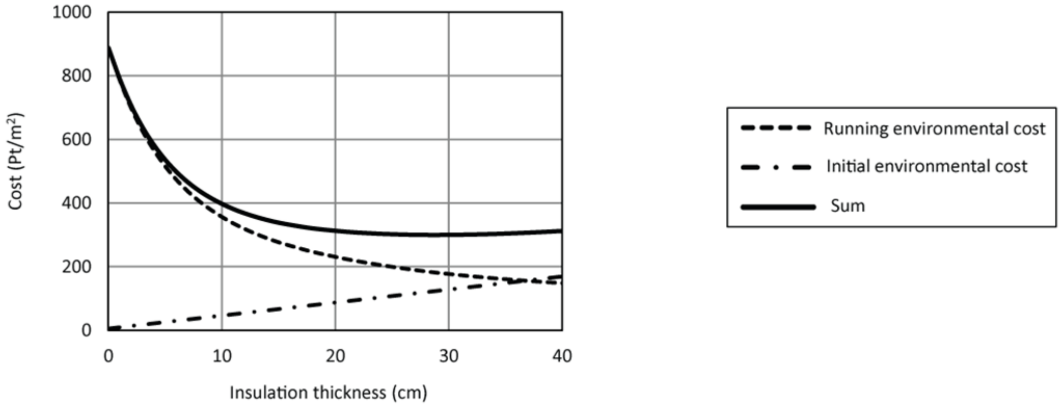
(a) CED

(b) IPCC 100



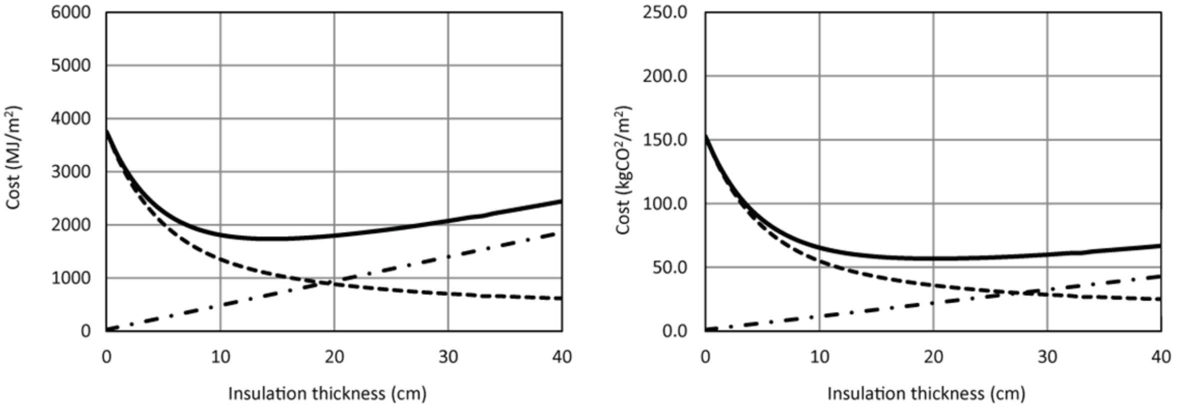
(c) IPCC 500

(d) Impact 2002+



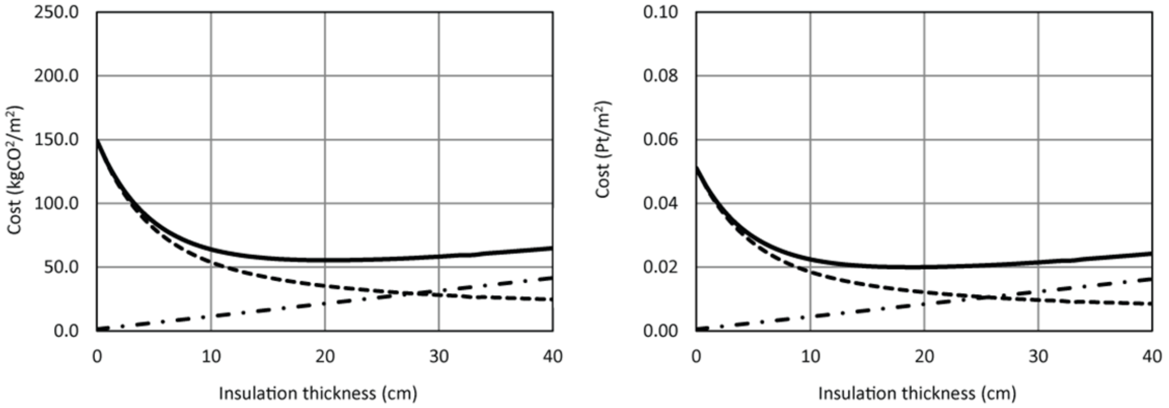
(e) Ecological footprint

Figure C-3: Ecological analyses for Morioka



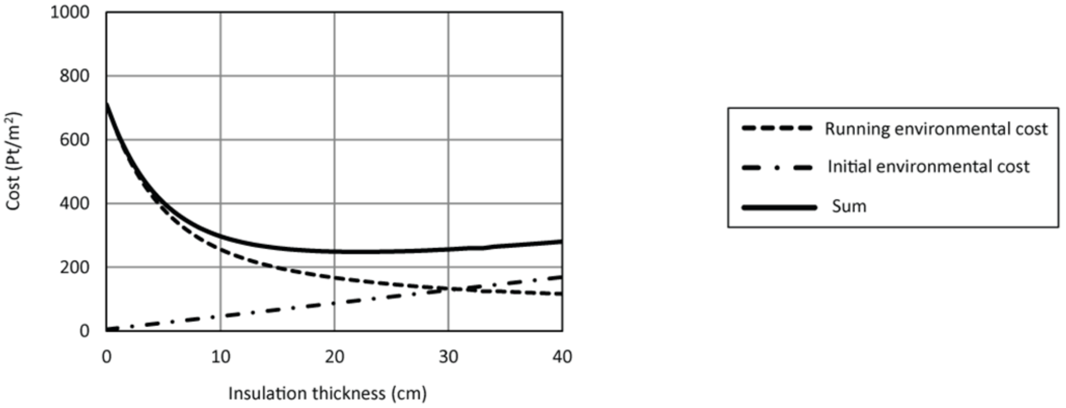
(a) CED

(b) IPCC 100



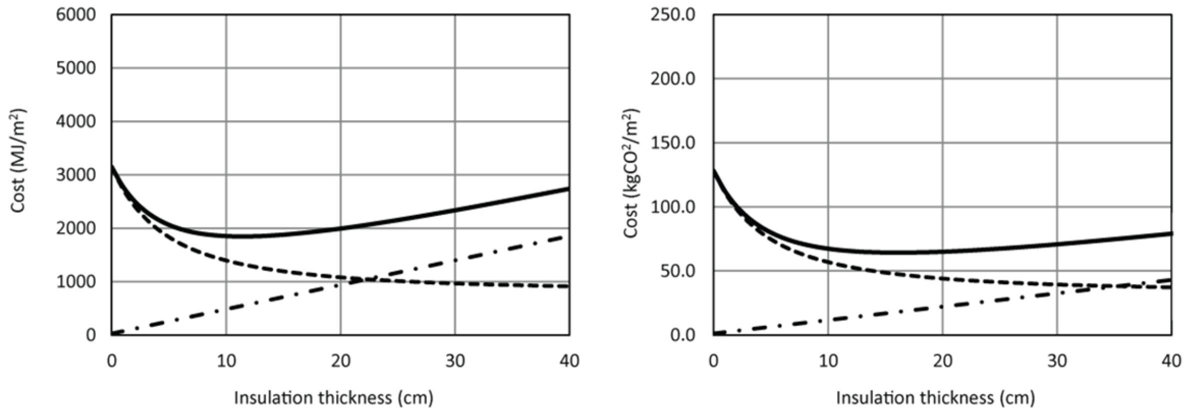
(c) IPCC 500

(d) Impact 2002+



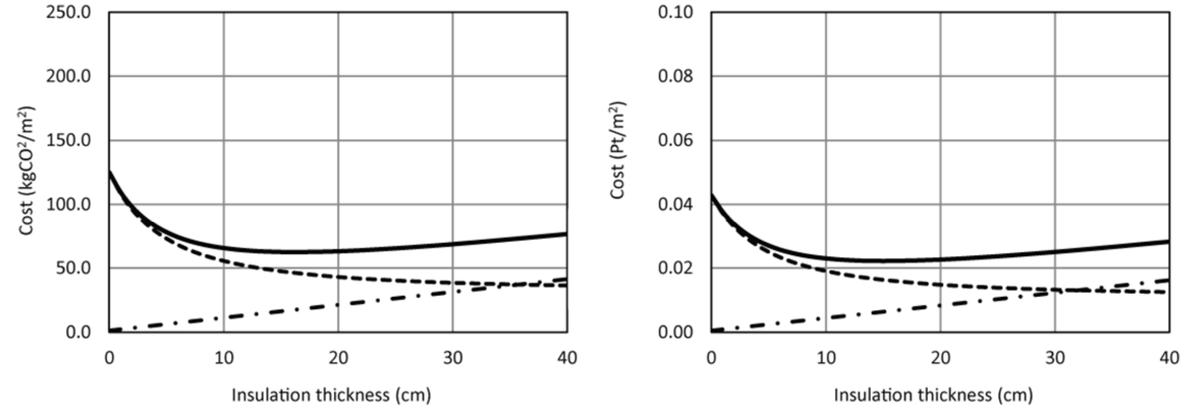
(e) Ecological footprint

Figure C-4: Ecological analyses for Sendai



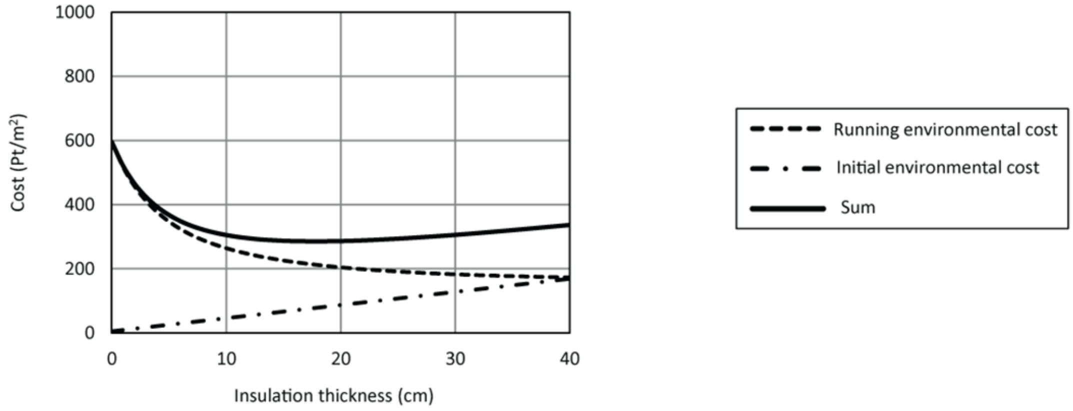
(a) CED

(b) IPCC 100



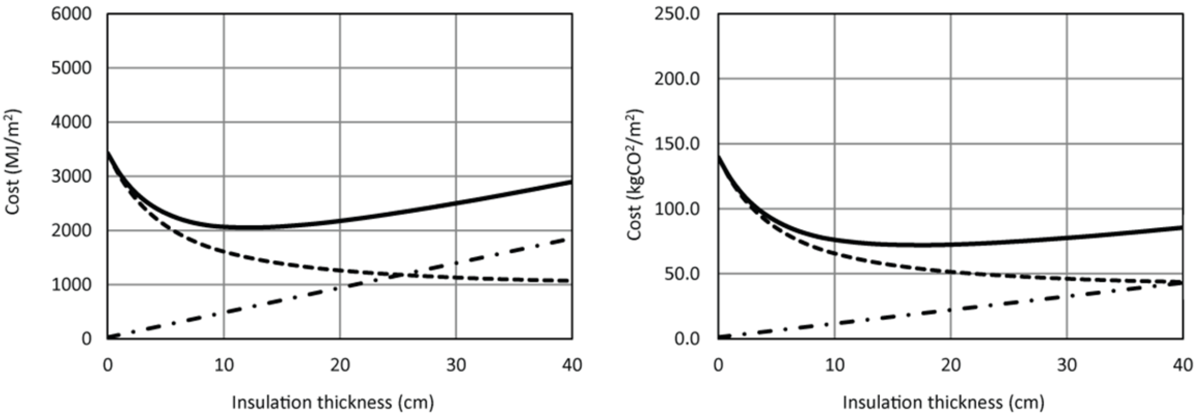
(c) IPCC 500

(d) Impact 2002+



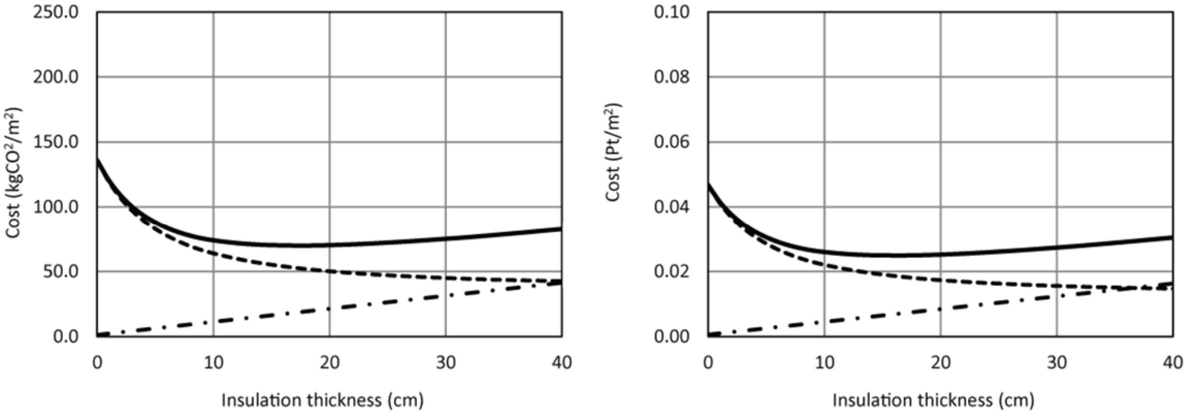
(e) Ecological footprint

Figure C-5: Ecological analyses for Tokyo



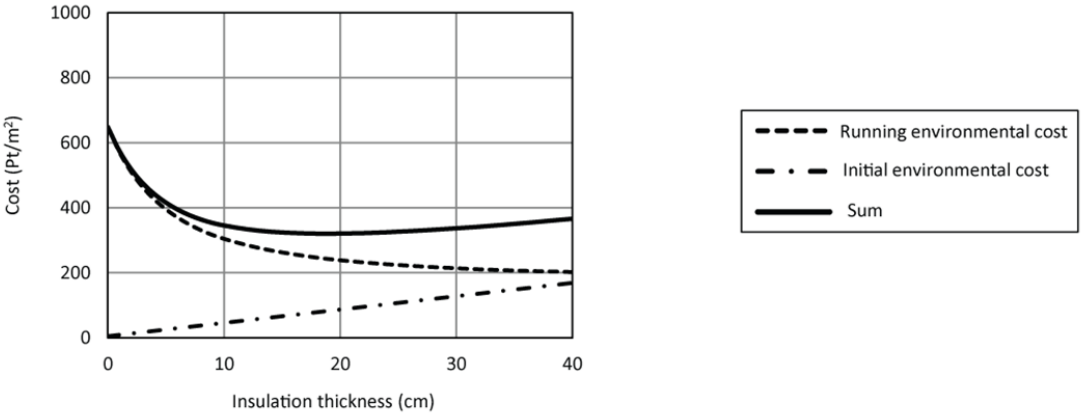
(a) CED

(b) IPCC 100



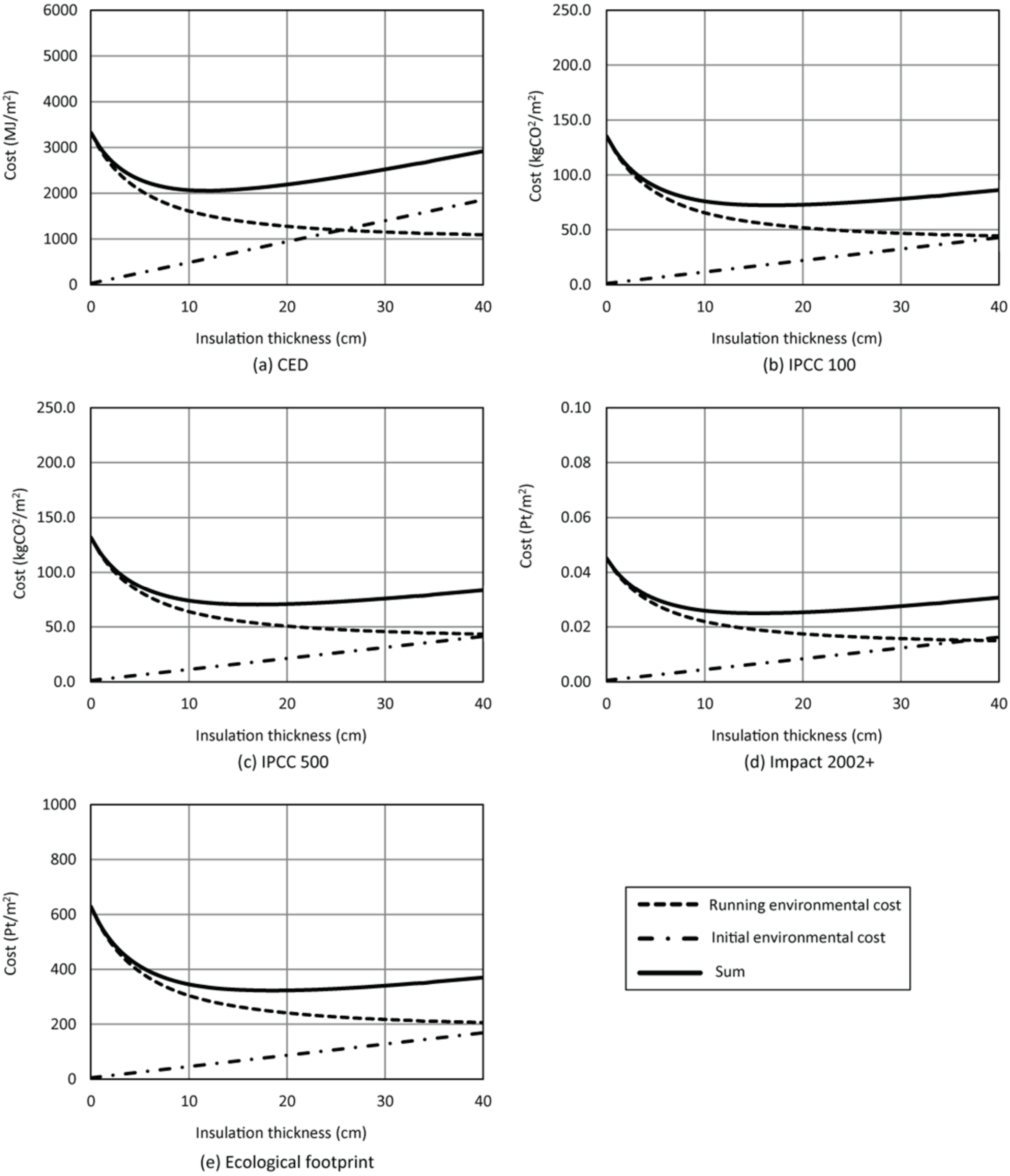
(c) IPCC 500

(d) Impact 2002+



(e) Ecological footprint

Figure C-6: Ecological analyses for Hiroshima



(a) CED

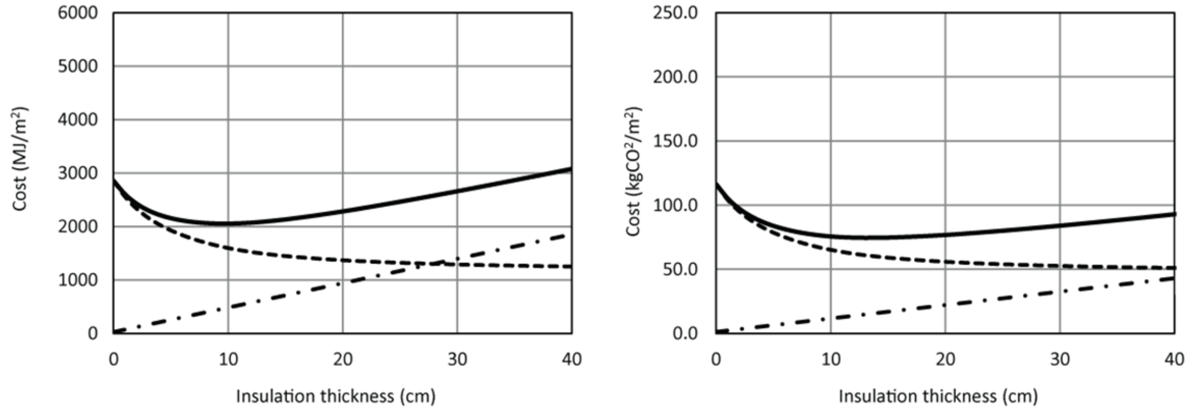
(b) IPCC 100

(c) IPCC 500

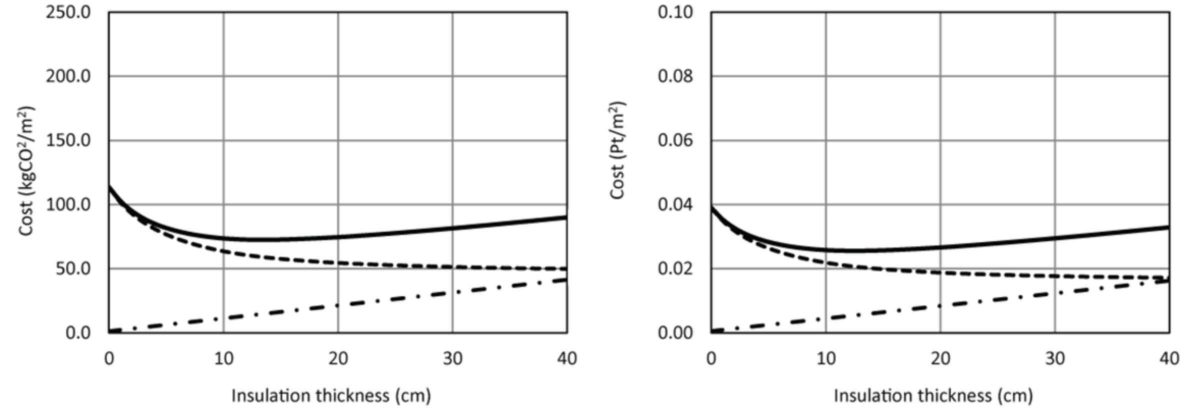
(d) Impact 2002+

(e) Ecological footprint

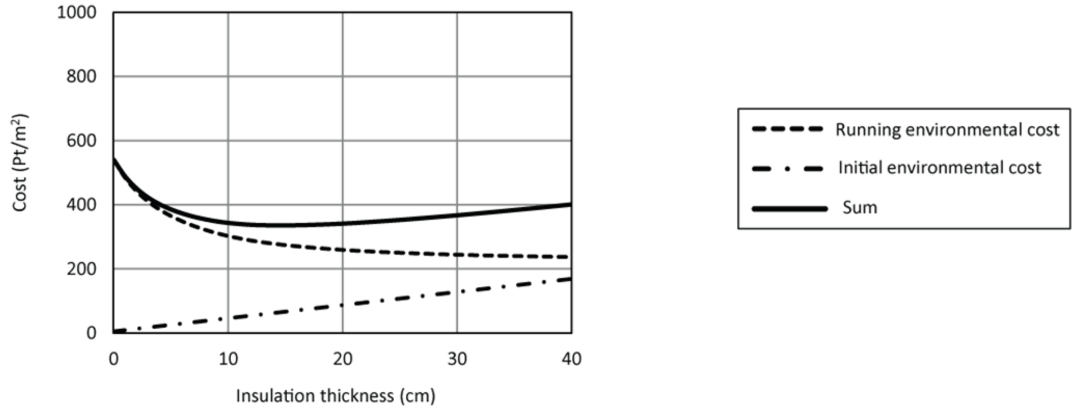
Figure C-7: Ecological analyses for Fukuoka



(a) CED (b) IPCC 100



(c) IPCC 500 (d) Impact 2002+



(e) Ecological footprint

Figure C-8: Ecological analyses for Kagoshima

The optimal 10% range for 5 indicators for 8 selected cities with the current energy mix is shown in Figure C-9 (see 5.3.3.3).

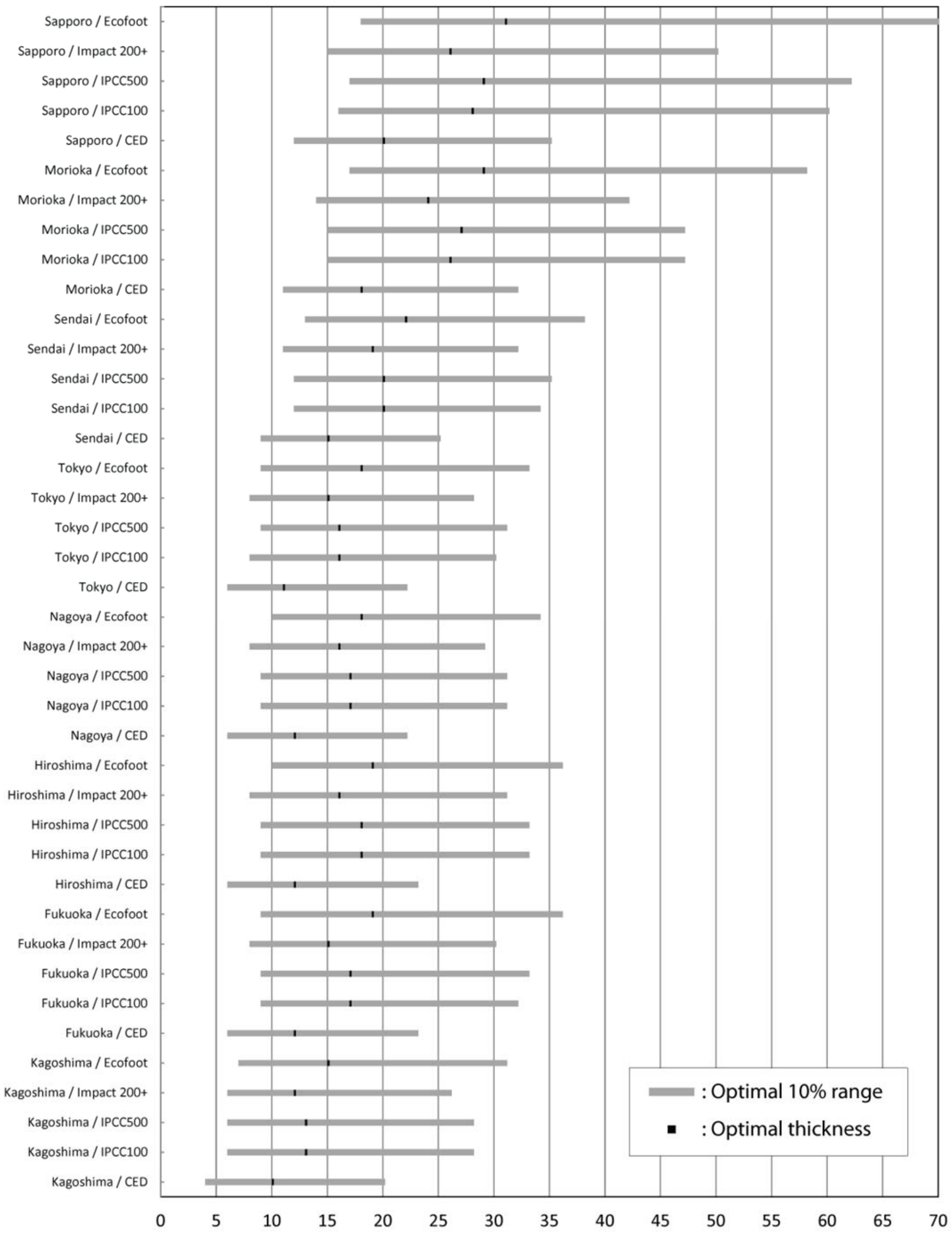


Figure C-9: Optimal 10% range for each indicator and for each city with current energy mix

The optimal 10% range for 5 indicators for 8 selected cities with energy mix 2030 is shown in Figure C-10 (see 5.5.2).

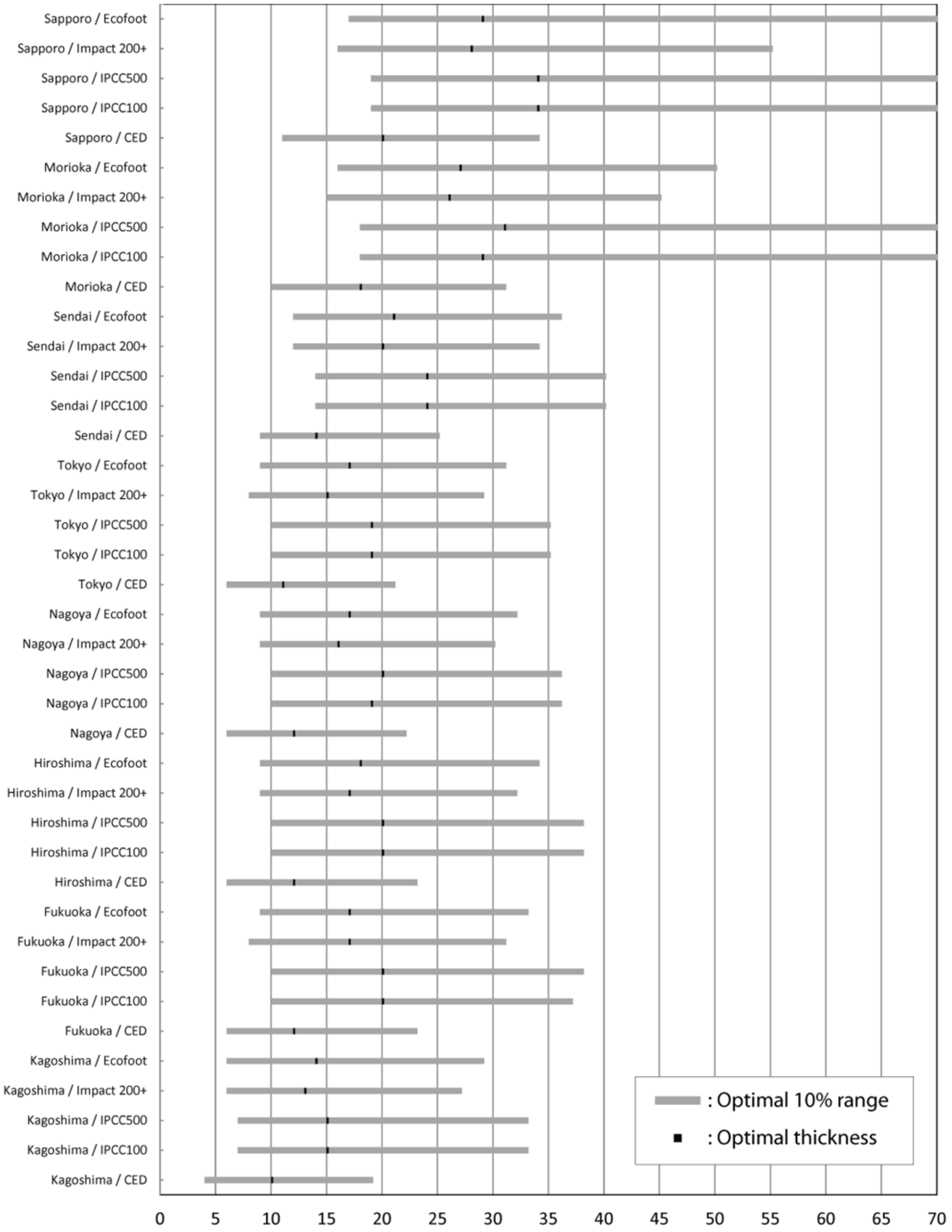
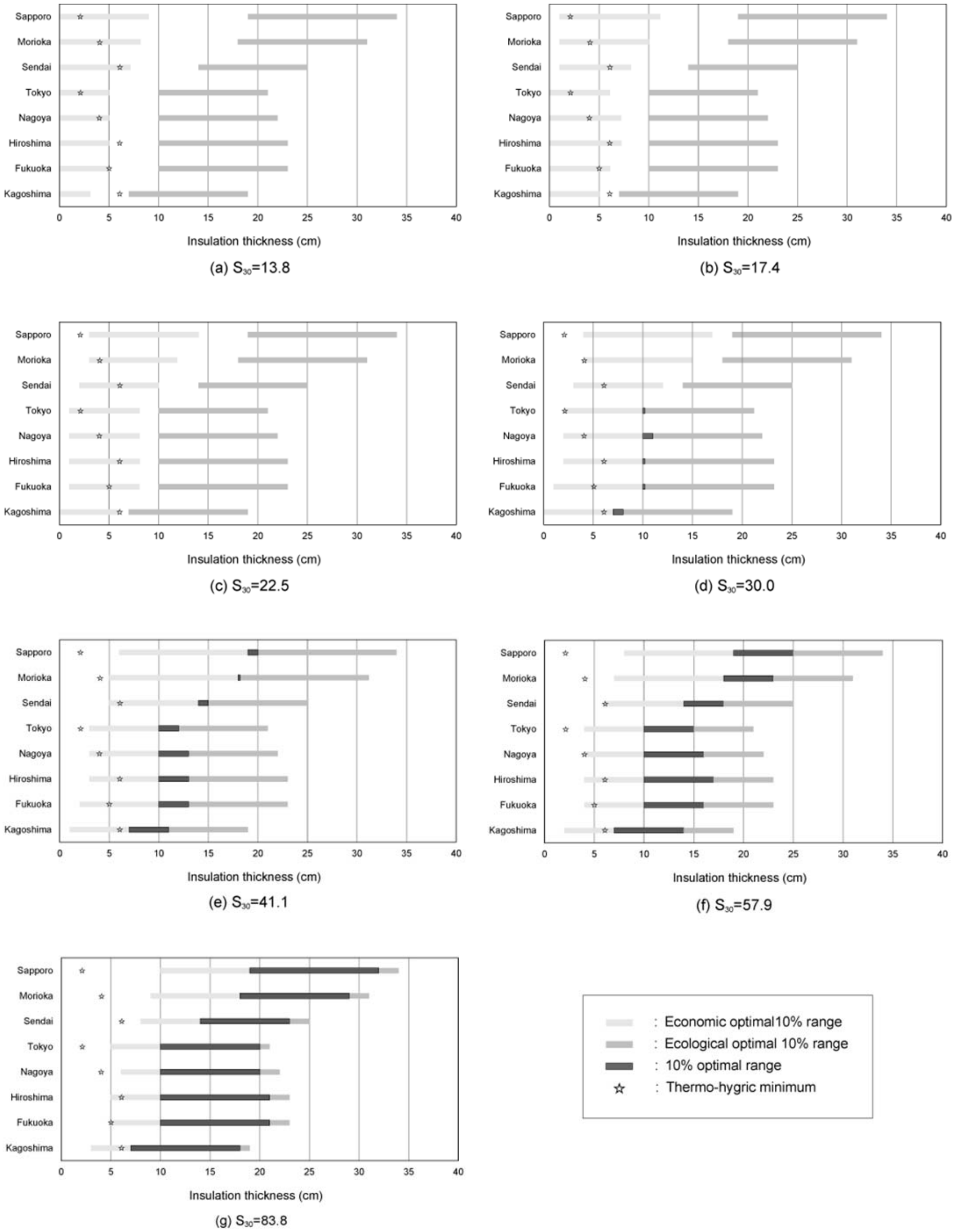


Figure C-10: Optimal 10% range for each indicator and for each city with energy mix 2030

The results of sensitivity study with 7 *S_{30}* Scenarios and energy mix 2030 are shown in Figure C-11 (see 5.5.2).



(a) S_{30}=13.8

(b) S_{30}=17.4

(c) S_{30}=22.5

(d) S_{30}=30.0

(e) S_{30}=41.1

(f) S_{30}=57.9

(g) S_{30}=83.8

Figure C-11: Optimal 10% range of the 8 cities with 7 S30 scenarios and energy mix 2030

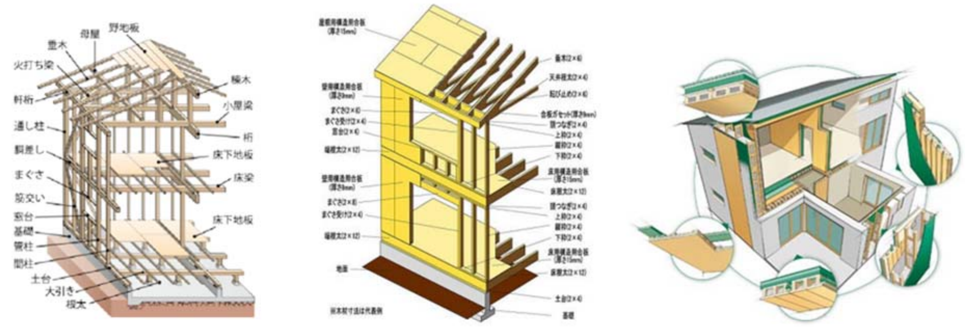
Appendix D - Comparison of CO_{2eq} emissions created by several alternative structural systems for Japan

D.1 Goal of the investigation

This Appendix presents the evaluation of the potential for saving CO_{2eq} emissions by establishing a local production of the cross laminated timber elements (hereafter called CLT) (see 2.1.4) using domestic wood (*sugi*) as an alternative to established wall systems using imported wood (softwood) in Japan. In addition to the investigation focused on CO_{2eq} emissions, the calculation for two accumulated indicators (ReCiPe and impact2002+) were also carried out in order to give an end point conclusion.

D.2 Background

The established systems in Japan (namely 2by4 and conventional post and beam) are very dependent on imported wood as the structural demands and required sections cannot be provided by regional wood (*sugi*). More than 70% of structural elements for those construction systems are provided by imported timbers (including plywood) (Forest Agency 2011). Meanwhile, the system proposed in this thesis allows to created wall elements from low quality and small sized wood by cross gluing them together and therefore could be applied for making those timbers profitable. A simplified section of the three systems is shown in Figure D-1.



Post and beam

Picture source:
http://am99.pa.land.to/list1035.html

2by4

Picture source:
http://am99.pa.land.to/list1035.html

The CLT proposed

Picture source:
http://www.lignotrend.de/

Figure D-1: Comparison of the three construction systems

D.3 System setting

The investigation compared the CO_{2eq} emissions resulting from the structural system of a house of typical size in Japan (60m^2 and two stories). The calculation is from cradle to gate (e.g. the final result is the finished structural system on site.

There are some limitations to this setting. The three houses will not be performing exactly equal in all settings. The calculation assumes the Japanese standard for structural demands as the relevant guideline. All three houses fulfill the demands of the standard. Another limitation is the running consumption of the house that is neglected in this analysis. Even when looking on current international top standards the running consumption in residential houses still is responsible for around 50% of the emissions over the lifecycle (Marceau et al. 2006). However the insulation level chosen is not directly linked to the construction system chosen. It has to be stated that some of the structural systems allow easier application of insulation than others and therefore have more potential to archive low running designed in a way that allows for easy application of consumption. With this regard the envelope system proposed in this thesis has a great advantage because of its layered structure.

D.4 Inventory analysis

All data on production processes are taken from the database Ecoinvent 2.2 (SCLCI 2011). The processes have been connected using the software SimaPro V7.3 (PréConsults). The frame conditions are listed below.

D.4.1 The construction systems

There is a significant difference in the amount of material used among the three construction systems. Apart from pure construction wood the 2by4 system and the post and beam need secondary elements for archiving structural capacity. For the 2by4 systems plating with plywood is mandatory. The complete envelope constructed by 2by4 therefore has to be plated with plywood by 100% (excluding windows). The post and beam system is more flexible in the way structural stability is archived. Possibilities range from bracing the frames with wood or steel to plating with plywood. Basically each company has its way of working within the post and beam system. For this report plating with plywood is assumed. Contrary to the 2by4 system the plating of walls does not have to be 100% of the envelope within the post and beam system. At the same time, the current trend of the post and beam construction is that companies have been starting using rather thick (24 or 28 mm) plywood as floor element ensuring the high level of rigidity of the floor structure and short construction time. In short, there are unlimited ways of using plywood in a post and beam construction. Therefore it is very difficult to estimate the amount of wood as structural element in a post and beam construction. Nevertheless, in this study it was assumed that the one-side wall plating of 60% and the thick plywood is applied to the floor plating of 100%, which counts the 70% the plywood used compared to 2by4 system. The system with the proposed CLT elements does not need any secondary elements.

The amount of material used to construct the structural components of a typical house in Japan is listed in Table D-1. The amount is given in kg of wood per m^2 of footprint of the house (e.g. 60 m^2 for a two story house of 120 m^2 net floor area). Density of construction wood was assumed to be 450 kg/m^3 and 780 kg/m^3 for plywood. As this investigation is only a simplified calculation, the joining components (steel plates, nails, glue) are neglected. Previous evaluations have shown that their impact is less than 5%.

Table D-1: Amount of wood and plywood for each construction system

	Material	
Construction system	Construction wood (kg/m^2)	Plywood (kg/m^2)
Post and beam	86.0	23.5
2by4	70.4	33.5
CLT	276.4	-

Source: own calculation based on reference scenario and statistical data from Japan Wood-Products Information & Research Center and Construction Ministry of Japan

D.4.2 Material data

Two ways of importing wood to Japan have to be analyzed separately. Logs are imported as cut trees and are manufactured in Japan. Lumber is wood that is cut and manufactured in the respective countries and imported as final product. The statistics of those are listed in Table D-2 and D-3 respectively. For the calculations the data from 2010 is used which is the most current data that was available.

Table D-2: Amount of imported logs from 2008 to 2010

		Log					
		2008		2009		2010	
		Amount (1000m^3)	%	Amount (1000m^3)	%	Amount (1000m^3)	%
North America	USA	1971	32	1671	40	1701	36
	Canada	774	12	760	18	1279	27
Russia		1867	30	693	17	447	9
New Zealand		842	14	521	13	737	15
Europe	Sweden	0	0	0	0	0	0
	Finland	0	0	0	0	0	0
	Others	41	1	35	1	30	1
China		5	0	6	0	5	0
Others		-	11	-	11	-	12

Source: Forest Agency

Table D-3: Amount of imported lumbers from 2008 to 2010

		Lumber					
		2008		2009		2010	
		Amount (1000m^3)	%	Amount (1000m^3)	%	Amount (1000m^3)	%
North America	USA	260	4	283	5	391	6
	Canada	2644	41	1959	35	2318	36
Russia		715	11	730	13	747	12
New Zealand		170	3	79	1	124	2
Europe	Sweden	598	9	747	13	743	12
	Finland	710	11	613	11	623	10
	Others	702	11	672	12	898	13
China		117	2	115	2	104	2
Others		-	8	-	8	-	7

Source: Forest Agency

These two ways of importing wood have to be progressed differently, as the production process efficiencies differ from country to country. The main driver for this is the energy mix of the respective countries. For countries for which exact data was available within the Econinvent data base this was used. In all other cases the energy mix was taken from the respective countries and applied to the production process for the construction wood.

Table D-4 shows the amount of corresponding statistics data for plywood.

Table D-4: Amount of imported plywood in 2006

		2006	
		amount in 1000 m^3	Percentage (%)
Foreign production (56%)	China	344.1	8
	Malaysia	2451.6	57
	Indonesia	1419.3	33
	Others	86.0	2
Produced in Japan (44%)	Russia	1855.8	56
	Japan	729.1	22
	Southeast Asia	662.8	20
	Others	66.3	2

Source: Ministry of Agriculture, Forestry and Fisheries, and Ministry of Finance

Plywood is partly imported as raw material and created in Japan and partly imported as a finished product. The only available data available was from 2006, therefore before the economic crisis. Current total number was assumed to be about 30% less. The distribution was assumed to be the same. The usage of plywood apart from plating is formwork for concrete. No data was available on whether certain sources of plywood are preferred for one usage or the other so an equal distribution was assumed.

D.4.3 Transport distance

The average transport distances for the respective countries were taken from common shipping routes. Transportation by truck was estimated for the individual countries according to statistical data when available or set to 100 km where no statistical data was available.

D.5 Calculations

As the goal of the study was to compare local production with the average impact of established systems in Japan, a material mix for construction wood and plywood based on the material data and the transport data was calculated. The results for the material mix are listed in Table D-5. For a typical house (gross floor area of 120 m^2) applying the material demand according to the respective systems, the calculated numbers are listed in Table D-6.

Table D-5: Environmental impact of using each structural element for each indicator

	CO_{2eq} (kg/kg)	ReCiPe (mPt/kg)	Impact2002+(µPt/kg)
Imported construction wood	0.35	111.6	287.6
CLT with domestic wood	0.15	60.2	52.9
plywood	3.41	736.5	1781.8

Table D-6: Environmental impact of using each structural in a typical house (gross floor area of 120m^2) constructed with each system for each indicator

	CO_{2eq} (ton/house)	ReCiPe (kPt/house)	Impact2002+ (Pt/house)
2by4	7.66	1.94	4.77
Post and Beam	7.60	2.08	5.19
CLT based	2.40	0.99	0.87

Figure D-2 shows the reduction of CO_2eq emissions by the use of CLT elements with domestic woods in comparison with the 2by4 and post and beam systems with imported woods. The CLT element can potentially reduce the CO_2eq by 71% and 62% compared to 2by4 and post and beam systems respectively.

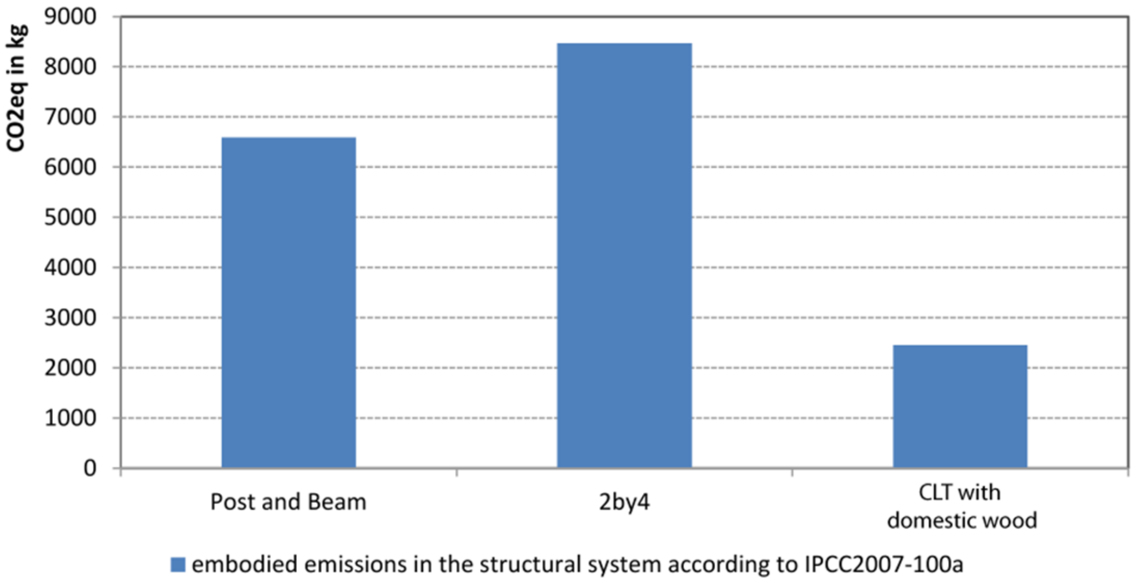


Figure D-2: Comparison of CO_{2eq} emissions among the three constructions systems

D.6 Discussions

It is clear that the use of locally produced structural systems using regional wood is producing the least amount of CO_{2eq} emissions. The main driver for emissions of systems using imported wood is the transport. The optimization potential in this area is low as transport distances are set and rather efficient transport means are assumed already. The results are supported by endpoint assessment via ReCiPe and impact2002+.

Plywood plays a significant role in the calculation. This can be related to the use of glues and high energy demanding process (hot press) on its production. In addition almost 90% of the plywood is imported increasing its associated CO_2eq emissions. The ability to avoid the use of plywood is a strong argument in favor of the deployment of the CLT elements with domestic woods from the environmental point of view.

There are several future enhancements that will improve the exactness of the investigation. The masses for the transport do not reflect the differing densities for log and lumber so far. It has to be assumed that the density of lumber as being already dried is lower per service unit than for logs. In order to reduce the transport impact it can be argued to only transport manufactured and dried wood. This will partially be compensated by more effective manufacturing procedures in Japan especially when the wood is coming from less industrialized countries.

A certain share of the logs imported to Japan will actually be waste wood after the manufacturing. No data on the amount of waste was available nor the exact treatment of this waste wood in Japan. Very often this wood is used in the drying process of the construction wood, offering a very environmentally friendly alternative to non-renewable energy carriers. This should be taken into account in the calculation.

Furthermore, the joining materials should be included in the future. Preliminary findings show that these parts make up less than 5 % of the total impact. The change of the results is probably very low, as similar joining components for all three systems are applied.

D.7 Conclusion

The use of domestic woods in Japan offers a great potential for reducing CO_{2eq} emissions. As the majority of detached houses are wooden constructions in Japan, any concept or product allowing the creating of structural systems for housing with domestic woods contributes to the climate change mitigation. The use of the CLT elements with domestic woods has a high potential to reduce CO_{2eq} emissions, while it has a significant economic merit that it could add values to unprofitable small sized woods.

D.8 References

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Appendix E - Sustainability evaluation of Test House by CASBEE

E.1 Goal of the investigation

This Appendix presents the sustainability evaluation of the Test House by CASBEE (Murakami et al. 2004) (see 1.1.3 and 1.2.4.1) in order to investigate the objective value of the building under the Japanese frame work. As a precondition, it should be noted that the discussion was limited within the design phase out of the four major phases of a construction (design, construction, operation and demolition phase).

E.2 CASBEE

CASBEE (Comprehensive Assessment System for Built Environment Efficiency) is a sustainability evaluation tool for buildings which was developed and has been used in the Japanese market. Therefore all the evaluation criteria are set in accordance with Japanese building/energy laws, regulations and customs. The main focus of CASBEE is on ecological aspects. Social and economic aspects of sustainability are less emphasized. CASBEE was developed according to the following policies (IBEC):

(1) The system should be structured to award high assessments to superior buildings, thereby enhancing incentives to designers and others.

(2) The assessment system should be as simple as possible.

(3) The system should be applicable to buildings in a wide range of applications.

(4) The system should take into consideration issues and problems peculiar to Japan and Asia.

CASBEE consists of following tools; CASBEE for Temporary Construction, CASBEE for New Construction, CASBEE-HI (for the assessment on the efforts in alleviating the heat island phenomenon), CASBEE-UD (for the assessment on the efforts of regional scale development) and CABEE-H (DH) (for the assessment for detached houses).

The result of CASBEE is given as the combined scores of environmental quality and performance (Q) and of environmental loadings (L). Q has three issues; Q1 indoor environment (with 10 criteria), Q2 quality of service (with 10 criteria) and Q3 outdoor environment on site (with 5 criteria). Each issue gets score of 0 to 5 which is the sum of the weighted score of its criteria. Then the score of Q is gained by summing the weighted score of the issues (the weighting factor is as follows; Q1=0.45, Q2=0.3, Q3=0.25). L also has three issues; LR1 Energy (with 15 criteria), LR2 resource and materials (with 14 criteria) and LR3 off-site environment (with 5 criteria). Each issue gets score of 0 to 5 which is the sum of the weighted score of its criteria as with the Q. The score of L is gained by summing the weighted score of the issues (the weighting factors are as follows; LR1=0.35, LR2=0.35, LR3=0.3). The characteristic point of CABEE compared to the other sustainability evaluation tools is that it takes into account the balance of the Q and L. By introducing the parameter BEE (Building Environmental Efficiency), the building's sustainability is quantified in a more rational manner (a building which has very little environmental load with very poor indoor quality is classified in a lower level). BEE is given by equation (E-1).

$$\mathit{Building\ Environmental\ Efficiency\ (BEE)} = \frac{\mathit{Q\ (Building\ environmental\ quality\ and\ performance)}}{\mathit{L\ (Building\ environmental\ loading)}} \qquad \text{(E-1)}$$

The final result is illustrated based on BEE. An example illustration is shown in Figure E-1. Buildings are graded according their BEE values. The best practice is grade S (BEE is higher than 3.0 and Q is in the range of the better half) and the worst is grade C (BEE is lower than 0.5). Furthermore the evaluation by CASBEE also gives the rough estimation of life cycle CO_2 ($LCCO_2$) based on the input information in the case that no in depth $LCCO_2$ data is available.

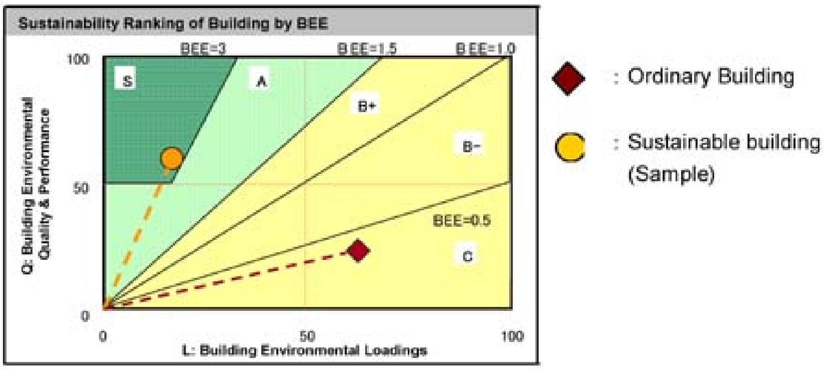

Figure E-1: Illustration of CASBEE evaluation

In the present investigation, the full version of CASBEE-H (DH) was used for evaluating Test House. This means that the design futures were examined substantially by the Japanese laws, regulations and customs. Although CASBEE is fundamentally a tool for carrying out evaluations by a third person, the evaluation was completed subjectively and was not verified by a third person. Regarding the criteria in which the required information to evaluate could not be found, the intermediate-value score were assigned because such score is designed to represent the least requirement of the standard quality buildings. The examples of such criteria are as follows; Q1.2.2.3 (security issue), Q1.4 (acoustic insulation), Q2.1.1.5 (installation of fire alarm), L1.2.3 (energy efficiency of appliances) and so on.

E.3 Result

The chart of the CASBEE evaluation is shown in Figure E-2. According to the setting of CASBEE, the score of 3 stands the standard level on each issue. The average score of all the issues was 3.9. The scores of all the issues were more or less the same (Q1 and L3 were somewhat higher than the other scores). The BEE was 2.6. This means that Sample House was classified into grade A which is the second best of the five grades.

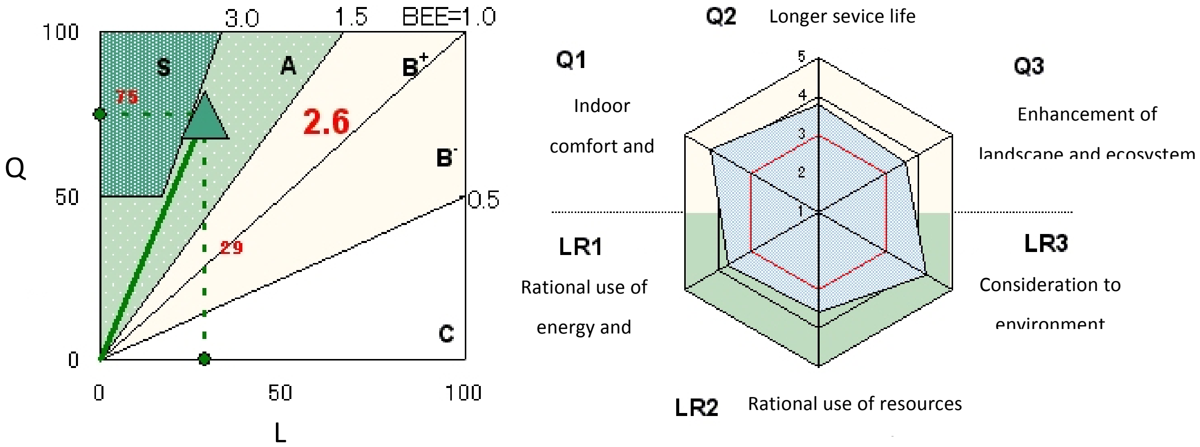

Figure E-2: The result of CASBEE evaluation

E.4 Discussion

E.4.1 Discrepancy in the evaluation

Although the evaluation was carried out subjectively, the assignment of the score was very clear and simple, therefore the result would not differ even when a third person carries out the evaluation. However, there was a certain difficulty when assigning the scores. Those were because of the fundamental discrepancy between the design consideration and the basic idea of the Japanese laws, building regulations and customs.

The most problematic discrepancy was about the heating/cooling system. Test House did not meet the given standard since it has a substantially different heating/cooling system than Japanese conventional houses.

What is set as prerequisite in the criteria of Q1.1.2.2 (Adequate cooling system) , Q1.1.3.1 (Adequate heating system), LR1.2.1.1 (the efficiency of heating system) and LR1.2.1.2 (the efficiency of cooling system) is that the buildings are supposed to use a heating/cooling unit installed in each room. Those criteria specify the level of adequacy based on the ratio of the capacity/efficiency of the air conditioners and the volume of the rooms. The worst grade is obtained when nothing is considered in the living room. The intermediate grade is obtained when the adequate measure regarding those items is taken in the living room. The best grade is obtained when the adequate measure is taken in the living room and bedrooms.

As a matter of fact, the criteria give the option to use heating/cooling device (e.g. radiator) other than normal air conditioners. In such cases, the conditions which can fulfil the requirement of “adequacy” are that (1) there is no big temperature distribution in the relevant rooms and (2) it is possible to control the temperature deliberately. However, those conditions are relevant not only to the design of heating/cooling system but also to the performance of the building envelope, that of the windows and the setting of mechanical ventilation system. Even if the heating/cooling system itself is not fulfilling those requirements, the performance of the building can be still good enough with a sound envelope solution. There could be a building whose envelope and housing services are designed well and whose heating/cooling system is rather at a small scale. This building might not have any heating/cooling device in the bedroom but it could have high level of thermal comfort, which is the case of Test House. This is a very clear example that an innovative idea, which is often largely different from conventional solutions, is not covered by an existing evaluation method.

Another problematic discrepancy was that the weighting factors did not seem to be set appropriately. For example, the performance of the envelope (its thermal resistance including the windows and the floor) and the consideration of the solar gain were weighted evenly. In fact, this weighting makes sense considering the conventional poorly insulated housings in Japan since the solar gain in winter can robustly cover the heat loss through the envelope. However, if transmission heat loss is minimised by an appropriate envelope design, the effect of solar gain is not as important as the case of the poor envelope. In this case, the percentage of the reduction of the energy consumption by heat gain is no longer the point to be evaluated. In order to evaluate well-insulated buildings, there is a clear need that the weighting factors in this issue are changed. Generally speaking, there should be the flexibility with the setting of weighting factors concerning the adaptation to innovative technological features.

Figure E-3 shows the result assuming that the problems mentioned above are solved in the following manners; (1) the criteria on the heating/cooling system allow the evaluation with the consideration of integrated building design which results in the small scale heating/cooling device, (2) the weighting factor for solar gain is optimised (actually the weighting factor cannot be changed technically, so the best score was simply assigned for this criterion). It is clearly shown that Sample House was evaluated more reasonably (better BEE value) considering the fact that Test House has far better energetic performance compared to the Japanese energy code (see 5.2).

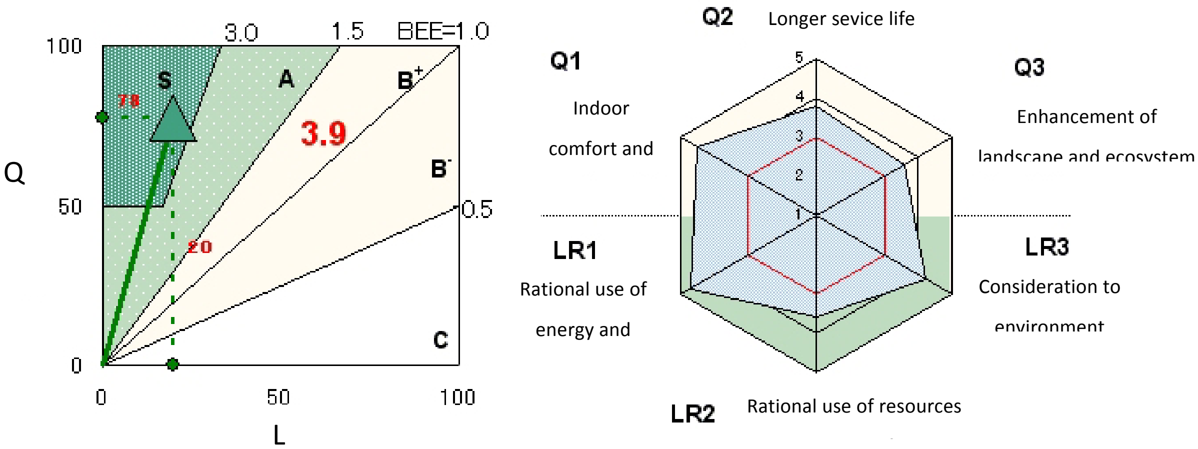

Figure E-3: Modified CASBEE evaluation

CASBEE should have certain flexibility in the evaluation method in each criterion. This would leave the space for innovative technologies to be implemented in the market. There should also be the possibility to change the weighting factors. The important point is that the arbitrary setting of the weighting factors must be able to be verified by a third person. To do so, CASBEE should provide a guideline of creating the new setting of weighting factors. It is necessary to develop such universal method to adopt those to the design condition not only of social contexts but also of technological features of the buildings.

As long as the evaluation method of CASBEE is not modified, buildings with the envelope system proposed in this thesis would have a major conflict with such a certification. Such a conflict actually represents the degree of difference between the conventional and innovative way of building design. The conflict might be translated into the less social acceptance by users as the frame work of the evaluation is based on the Japanese conditions and thinking in terms of buildings. The advantage of innovations should be well explained to both users and practitioners in order to avoid misunderstandings derived by conservative fixed thinking.

E.5 Conclusion

In the present investigation, Test House was evaluated by the Japanese sustainability evaluation tool for buildings CASBEE. The following findings and conclusions were made:

1. Test House was classified into grade A which is the second best of the five grades.
2. The evaluation by CASBEE was reasonable because the basic frame condition is in accordance with the Japanese conditions. However, there were a fundamental discrepancy between the design consideration and the basic idea of the CASBEE evaluation.
3. Innovative ideas which differ a lot from the Japanese conventional solutions are not evaluated appropriately by the existing evaluation method of CASBEE.
4. The result by modified CASBEE, which assumed that the problems in the inflexibility are solved, evaluated Test House more reasonably.
5. CASBEE should have certain flexibility both in the evaluation method and the setting of the weighting factors in each criterion.
6. As long as the evaluation method of CASBEE is not modified, buildings with the envelope system proposed in this thesis would have a major conflict with such a certification. Such a conflict might represent a less social acceptance.

7. The advantage of innovations should be well explained to both users and practitioners in order to avoid misunderstandings derived by conservative fixed thinking.

E.6 References

IBEC: http://www.ibec.or.jp/CASBEE/english/overviewE.htm (accesses on 22/05/2012)

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